Power Electronics Semiconductor Devices
Edited by Robert Perret
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Chapter 3

Series and Parallel Connections of MOS and IGBT

3.1. Introduction

The development of power applications leads to increasing power requests on the electronic switches, used in power converters. These converters are able to flexibly control electrical power actuators, and are more frequently used in industrial applications than in consumer applications. Equipment powers are increasing, while costs for a given switched power are reduced (in pounds per Kilowatt), and the quantities produced are strongly enhanced.

In order to face these new challenges, engineers are focusing on:

– improvement of power components performances, especially on current and voltage ratings, together with speed ratings; and

– combined use of components, in order to increase capacities and the performance of these switches. This is a spontaneous idea, arising from the beginnings of power electronics. It may be applied to components, as it is applied to commutation modules, and whole converters.

This chapter focuses on the association of power components; however, these same methodologies may be used in a more general context.

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3.2. Types of associations

Association of components is used in order to increase performances in two ways.

3.2.1. *Increase of power*

This may be achieved by increasing commutated voltages or currents. In practice, increasing commutated power may be achieved by increase of the number of associated components. Three methods for increasing power are:

– *parallel* connection of components, to increase current ratings;

– *series* connection of components, to increase voltage ratings;

– *matrix* connection of components, which is a combination of the two former associations.

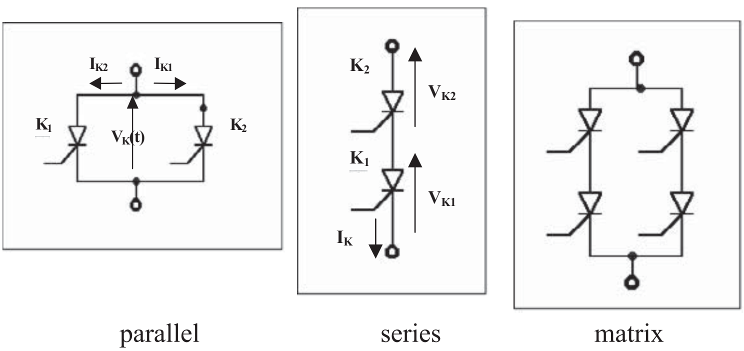


Figure 3.1. *Types of associations.*

These are *homogenous* associations: the spontaneous goal is an effective "sharing" of constraints between the associated components.

In all cases, the challenge for a good design is the effective control of the sharing of constraints between the different associated elements, in order to reach, as an ideal result, an equal distribution of constraints. Nevertheless, associations may be designed in order to simply maintain components inside their own domain of security (safe operating area), rather than to make a strict sharing. Associations may also have very different behaviors when facing overloads during fault operations: this is an important aspect for analysis of the different types of associations.

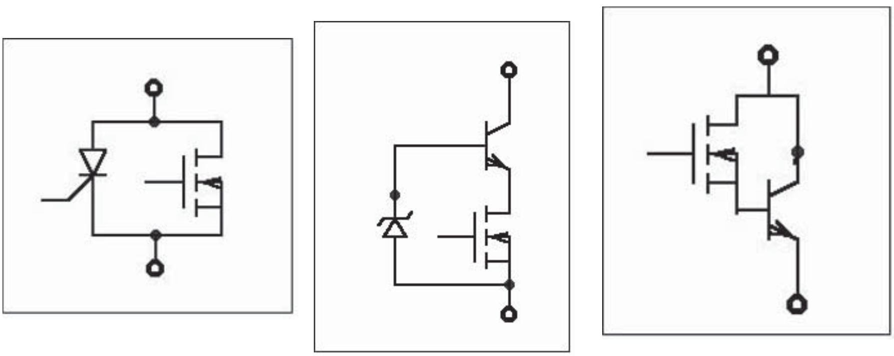
3.2.2. *Increasing performance*

This may be achieved by the association of components that have different characteristics, in order to take advantage of only the strong features of each one. Some cases to be mentioned are:

– parallel connection of a fast component (MOSFET) together with a low saturation voltage component (bipolar);

– series connection of a high voltage rating component, together with a low voltage but very fast component (Cascode design); and

– Darlington connection, which may be homogenous, like bipolar-bipolar, or heterogenous, for instance MOS-bipolar. This kind of association allows a self-supply of the drive current from the power.



Parallel Cascode Darlington

Figure 3.2. *Heterogenous associations of components*

These are *heterogenous* associations, where each element plays a specific role, corresponding to its strong feature.

In this chapter, we will study only homogenous associations.

3.3. The study of associations: operation and parameter influence on imbalances in series and parallel

3.3.1. *Analysis and characteristics for the study of associations*

The study of component associations has led to the knowledge of specific variables (currents and voltages), as a function of time, for each element of this association. In the field of power electronics, commutation cells are analyzed using two aspects:

– static operation, including two states: opened or closed (conducting); and

– dynamic operation, which occurs during commutation phases: closing and opening.

These studies require an internal approach, similar to that of a single component, taking into account different types of external conditions (imposed on the switch by its environment). For a simple approach, a presentation is made of the association of two switches, but conclusions may be applied to several elements [GUI 95].

3.3.1.1. *Parallel association*

Two basic relations may be written for parallel associations. The first relates to voltage:

$$V_{K1}(t)=V_{K2}(t)=V_K(t)$$

and ensures that the lowest voltage is imposed on the association.

The second equation relates to current sharing inside the association:

$$I_{K1}(t)+I_{K2}(t)=I_K(t)$$

Current sharing depends only on components and is the main study parameter for parallel connection.

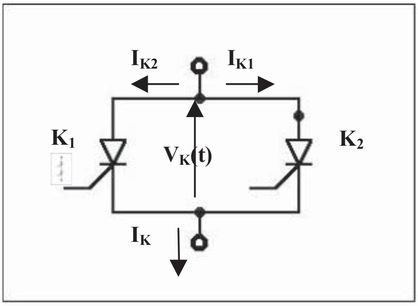


Figure 3.3. *Electrical laws for parallel association*

3.3.1.2. *Series association*

Series connection is dual in contrast to the parallel connection, this means the basic relations are also dual.

The first relates to voltage sharing inside the association:

$$V_{K1}(t)+V_{K2}(t)=V_K(t)$$

Voltage sharing depends only on the components.

The second relation involves currents:

$$I_{K1}(t)=I_{K2}(t)=I_K(t)$$

This means the lowest current is imposed on the association. Voltage sharing is the main study parameter for series connection.

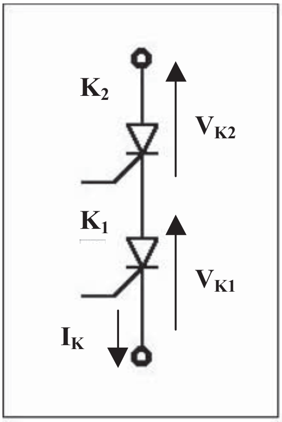


Figure 3.4. *Electrical laws for series association*

3.3.2. *Static operation*

There are two static states:

– during opened state, IK(t)=0 is defined by the switch, and VK(t)=Vext(t) is defined by the outside circuit; and

– during closed state, VK(t)=0 is defined by the switch, and IK(t)=Iext(t) is defined by the outside circuit.

3.3.2.1. *Parallel connection*

For this association, only the closed state must be analyzed, while, during open state, there is no mismatch of voltages by principle, and no mismatch of current because the current is zero.

The static characteristic of each component on closed state I(V), and the basic relationships, define the sharing of current between the two components, as is clearly depicted in Figure 3.5. We can see that the component with better (K_1) takes more current. In other words, the stronger component helps the weaker component.

Using a linear model like $V_K=V_0+RI_K$, the operating point of the association is defined by:

$$V_K(R_1+R_2)=(V_{01}R_2+V_{02}R_1)+R_1R_2I_K$$

The current imbalance is due to dispersions of static performances of components. This generally leads to the requirement of component selection, in order to limit dispersal of voltages at the current rating. The choice of components inside a single batch is a positive point in order to reach a better balance.

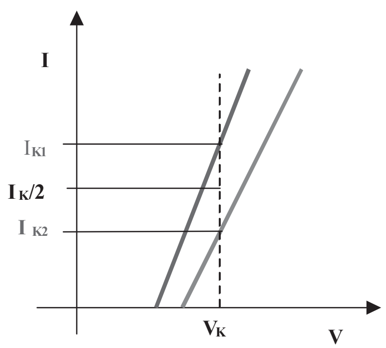


Figure 3.5. *Effect of different static characteristics on voltage sharing in a series association*

In order to take into account these unbalances, it is generally well suited to apply a reduction coefficient on the usable current rating, let us say a “derating”, which depends on the number of components connected in parallel.

3.3.2.2. *Series connection*

For this association, only the open state must be analyzed. As a matter of fact, at zero voltage, there is no mismatch of current by principle, and no mismatch of voltage.

The static characteristic on open state I(V) of each component defines the sharing of voltage between the two components, as seen in Figure 3.6. Here we can see the component with better voltage strength (K_1) takes more voltage; in other words, helping the weaker component.

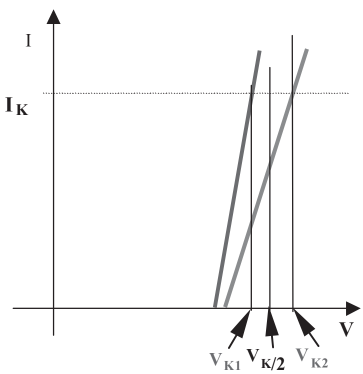


Figure 3.6. *Series connection*

Voltage imbalances in the open state are due to the dispersion of the characteristics of the components. It should be noted that the imbalance of static voltage occurs mainly at the start of the converter. This condition usually does not occur during operation, due to long time constants governing the passage of transient dynamic imbalance to the static imbalance. Figure 3.7 below shows this time constant is greater than 20 ms. In normal operation, this leads to a negligible imbalance of static voltage, of over a few hundred hertz, for a series connection.

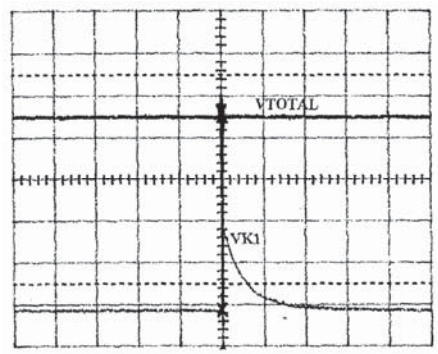


Figure 3.7. *Time constant from dynamic imbalance to static imbalance, for a large leakage current MOS, series connected with a low leakage current MOS. V: 100 V/div, t: 20 ms/div*

The classic solution achieves this balance with resistances connected in parallel on each component, reducing or eliminating this imbalance of voltages. An alternative solution is to use voltage limiters in order to maintain individual voltages within the safe operating area. In this case, balance is not achieved, but imbalance is limited in such a way as to ensure each component remains in its own safe area. We should note that most of the switches and diodes used in power electronics are able to support an avalanche with a low current, and therefore assure themselves this clamping function safely.

3.3.3. *Dynamic operation: commutation*

During dynamic operation phases, two main parameters drive the current imbalance (respectively voltages) in parallel connections (respectively series connections):

– on the one hand, delay time; and

– on the other hand, commutation speed. This speed is current speed (respectively voltage speed) for parallel connection (respectively series connection); while voltage (respectively current) is the same.

These two parameters are defined by basic relationships during dynamic phases. Commutation is analyzed in classic conditions of an elementary “hard” commutation cell.

3.3.3.1. *Closing process*

The initial conditions, applied on the switch before closing, are:

– a voltage defined by the external circuit (E);

– a zero current, while the switch is still opened.

During the closing process, while the switch is able to manage its own current, voltage is still applied on the switch, as soon as the diode of the cell is closed. Opening of the diode makes a change of mode: external current is then limited and voltage depends on the cell: this is the current external mode.

3.3.3.1.1. Influence of the delay time difference

For series, parallel and matrix connections, components must commutate synchronously, in order to limit imbalance of the electric parameters. There are two possible causes of delay between commutation orders. One is due to components (dispersion of characteristics), the other is external from components (dispersion of commutation orders delivered by drive circuits). It is assumed the two switches have the same speed, dI_K/dt, and a lack of synchronization, Δton.

Parallel connection

Lack of synchronization Δton makes an advanced overload on the switch, and an underload on its delayed partner. Overload is given by the relation:

$$2\Delta Ion=\Delta ton(dI/dt)$$

This phase is over at switch-off of the diode.

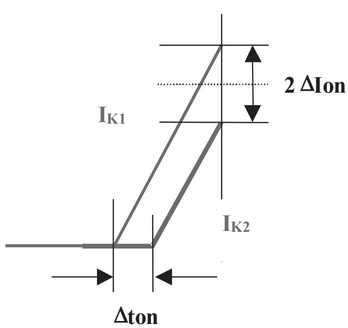


Figure 3.8. *Effect of a delay at turn on for the same current commutation speed in a parallel association*

Series connection

A voltage balance is assumed at initial time. The lack of synchronization Δton makes an overvoltage, which occurs before the current is able to increase.

Indeed, voltage of the switch in advance decreases; and in order to comply with voltage law, the voltage of the delayed switch increases. Current, except for capacitive current, will be able to increase when the two switches are closed. The overload value is given by the relation:

$$2\Delta Von=\Delta ton(dV/dt)$$

Speed of dV/dt depends on the internal capacitances of the components.

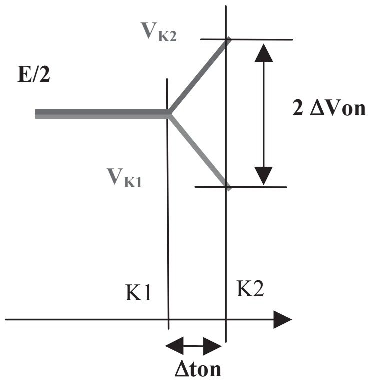


Figure 3.9. *Effect of a delay at turn on for the same voltage commutation speed in a series association*

MOS voltage depends on the delay Δt of the control (from 20 to 80 ns). The two other components are synchronous.

Figure 3.10 depicts the series connection of a three MOSFET switch-on where the scales are 100 V/div, 100 ns/div.

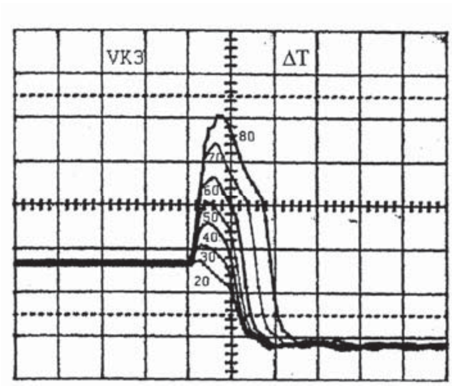


Figure 3.10. *Series connection of three MOSFETS – turn on*

3.3.3.1.2. Influence of speed dispersion

Dispersion between the characteristics of the components leads to differences between speeds current evolution and transient voltage. This leads to imbalances in constraint sharing. There is assumed to be a perfect synchronization and an initial sharing of constraints.

Parallel connection

As each component is free during current increase, it is able to define its own speed.

Difference of speed leads to an overload on the fastest switch and an underload on its slower partner. The overload value is given by the relation:

$$2\Delta Ion = Iext(\alpha_1 - \alpha_2)/(\alpha_1 + \alpha_2)$$

where $\alpha 1$ and $\alpha 2$ are current speeds of K_1 and K_2

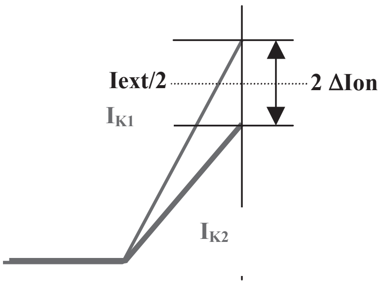


Figure 3.11. *Effect of a mismatch in current commutation speed at turn on in a parallel association*

Series connection

Here an initial balance of voltages is assumed. While this is a decreasing phase, speed difference between the two components does not lead to overload, however commutation losses will not be the same.

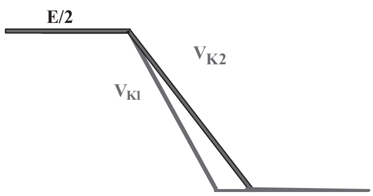


Figure 3.12. *Effect of a mismatch in voltage commutation speed at turn on in a series association*

3.3.3.2. *Turn off*

This is a dual commutation study which enables us to foresee results, by applying the rules of duality to former results. The initial conditions applied to the switch, before opening, are defined by the cell:

– a current applied by the external circuit (Iext);

– a zero voltage, since it is still not opened.

During opening, as current is imposed, the switch manages its own voltage as long as the diode of the cell remains opened: this is an external current mode. Closing of the diode makes a change of mode, thus external voltage is limited and the current depends on the cell: this is external voltage mode.

3.3.3.2.1. Influence of the difference in the delay time

The following assumes the two switches have the same speed, dV_K/dt, and a lack of synchronization Δtoff.

Series connection

Lack of synchronization in Δtoff leads to a voltage excess on the advanced switch, and an undervoltage on its associated partner. Value of the overload is given by the relation:

$$2\Delta Voff=\Delta toff(dV/dt)$$

This phase ends at switch-on of the diode.

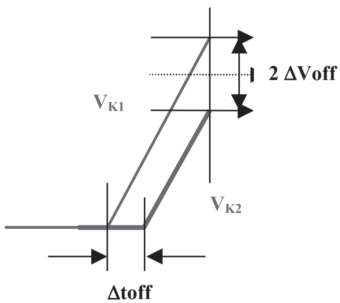


Figure 3.13. *Effect of a delay at turn off for the same voltage commutation speed in a series association*

Parallel connection

Here there is assumed to be an initial current balance. Lack of synchronization in Δtoff leads to an excess current before the voltage is able to increase. Indeed, the current inside the switch decreases in advance and, in order to respect nodes law, the current in the delayed switch increases. Voltage will be able to increase only when the two switches will be are opened. The value of the overload is given by the relation:

$$2\Delta Ioff=\Delta toff(dI_{K1}/dt)$$

Speed dI_{K1}/dt depends on the component and also on its command.

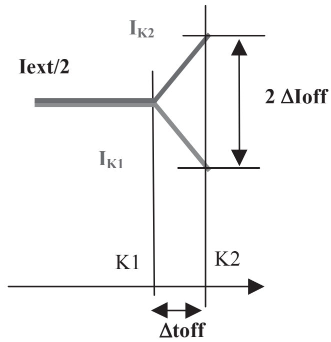


Figure 3.14. *Effect of a delay at turn off for same current commutation speed in a parallel association*

As shown below in Figure 3.15, MOS voltage depends on the advance Δt of its drive (from 15 to 40 ns); two other components are synchronous. Scales: 100 V/div, 2 A/div, 100 ns/div.

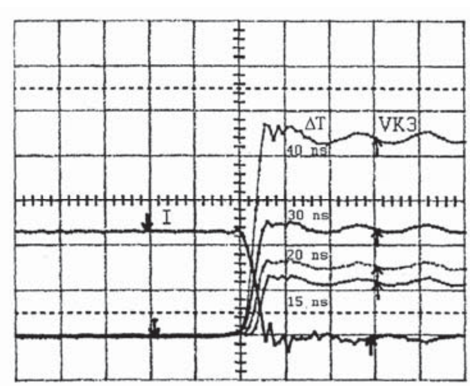


Figure 3.15. *Series connection of three MOSFETs – turn off (scale: 100 V/div, 2 A/div, 100 ns/div)*

3.3.3.2.2. Influence of the difference of speeds

Dispersion of component characteristics leads to varying speeds of current and voltage evolution during transient phases. This leads to imbalances in shared constraints. We assume synchronization is perfect, and the initial conditions are balanced.

Series connection

As each component is free during voltage increase, it defines its own speed.

Difference in increasing speeds leads to an overload on the fastest switch, and an underload on its slower partner. The overload value is given by the relation:

$$2\Delta Voff=E(\alpha_1-\alpha_2)/(\alpha_1+\alpha_2)$$

where $\alpha 1$ and $\alpha 2$ are voltage speeds of K_1 and K_2.

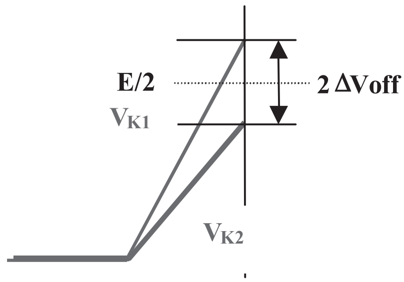


Figure 3.16. *Effect of a mismatch in voltage commutation speed at turn off in a series association.*

Parallel connection

Here an initial state of current sharing is assumed. Difference of speed between the two components does not lead to overloads, since this is a decreasing phase; but commutation losses are not the same.

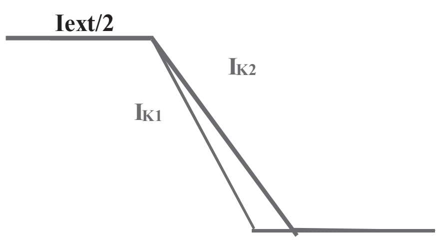


Figure 3.17. *Effect of a mismatch in current commutation speed at turn off in a parallel association*

3.3.3.3. *Synthesis*

	Parallel	Series
Turn on	– the anticipated switch is overloaded in current, helping the delayed one. – the voltage speed at turn on is the one of the slowest switch (algebraic value); – the fastest switch is overloaded in current, and it helps the slowest	– the anticipated switch is helped, overloading the other switch in voltage – current speed at turn on is the one of the slowest switch –the fastest switch (absolute value) is helped, overloading the other switch in voltage.
Turn off	– the anticipated switch is helped, overloading the other switch in current – voltage speed at turn off is the one of the slowest switch – the fastest switch (absolute value) is helped, overloading the other switch in current.	– the anticipated switch is overloaded in voltage, helping the delayed one. – the current speed at turn off is the one of the slowest switch (algebraic value); – the fastest switch is overloaded in voltage, and it helps the slowest

Table 3.1. *Summary of dynamic unbalance: delay and mismatch in commutation speed*

The following chart shows a more synthetic representation.

<table>
<tr><th colspan="2"></th><th colspan="2">Parallel</th><th colspan="2">Series</th></tr>
<tr><th colspan="2"></th><th>K1</th><th>K2</th><th>K1</th><th>K2</th></tr>
<tr><th rowspan="6">Closing (opening)</th><th>Synchronized</th><td>Advance</td><td>Delay</td><td>Advance</td><td>Delay</td></tr>
<tr><th>Current</th><td>Overload (Helped)</td><td>Helped (Overload)</td><td colspan="2">Zero (+ capacitive)</td></tr>
<tr><th>Voltage</th><td colspan="2">Vext (-V inductive)</td><td>Helped (Overload)</td><td>Overload (Helped)</td></tr>
<tr><th>Speed</th><td>Fast</td><td>Slow</td><td>Fast</td><td>Slow</td></tr>
<tr><th>Current</th><td>Overload (Helped)</td><td>Helped (Overload)</td><td colspan="2">One of the slowest</td></tr>
<tr><th>Voltage</th><td colspan="2">One of the slowest</td><td>Helped (Overload)</td><td>Overload (Helped)</td></tr>
</table>

Table 3.2. *Synthetic view for effects of delays and mismatch in commutation speed*

Duality may be seen from the points of view of:

– opening and closing;

– series and parallel;

– advance and delay;

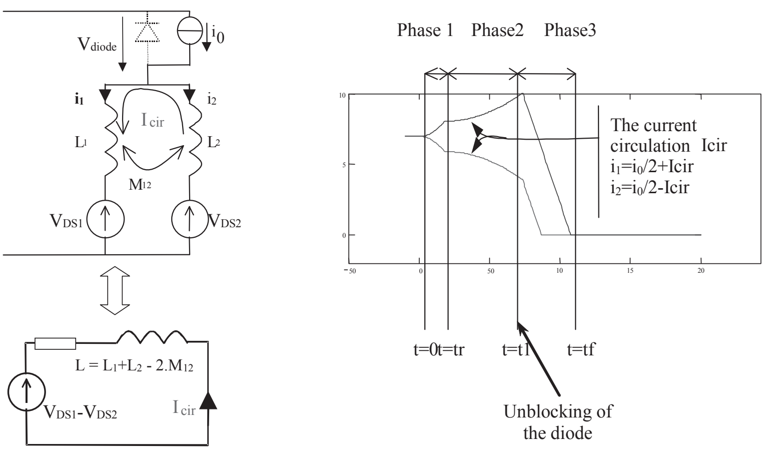
– fast and slow.

Advance and fastness have the same effect, as, by duality, delay and slowness have the same effect. Thus, results are the same for the advanced or the fast components, and, by duality, for delayed or slow components.

3.3.4. *Transient operation [JEA 01]*

Inside a parallel association of components, during a commutation, occur phenomena which lead to transient imbalances, due to causes other than different commutation speeds of current. Indeed, during evolution of voltages across semiconductors, if they are different, an internal current inside the association is generated, due to the difference of voltages between the semiconductors.

During opening, this phenomenon is strong because the voltage commutation occurs *before* the current commutation. A loop current is added to the power current defined by the load [JEA 01]. Even before the beginning of the current commutation, this transient voltage leads to an imbalance, (see Figure 3.18).



(a) : Equivalent schematic for a loop current

(b) : Theoretical waveforms for currents i1 and i2 at opening.

Figure 3.18. *Loop current during opening*

Despite what is seen above in the equivalent schematic, this current is not limited by the "inter-switches" wiring inductance, because it compensates for the difference of voltages. As a matter of fact, with no wiring inductance, there is no voltage difference, and thus no loop current.

This is supported by Figure 3.19, which shows the evolution of the loop current amplitude at opening, as a function of "inter-switches" inductance.

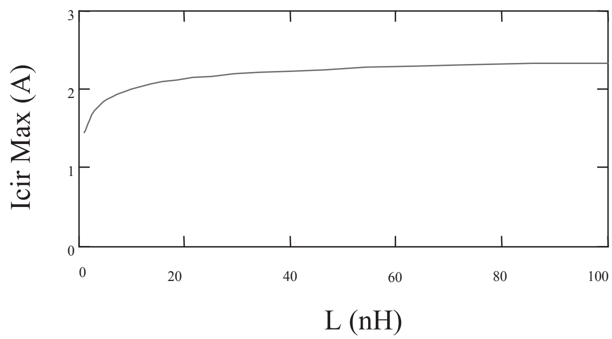


Figure 3.19. *Evolution of maximum value of loop current as a function of L , with r_{G1}=9.9Ω, r_{G2}=10.1Ω, Crss1=130pF and Crss2=140pF*

During closing, current evolution takes place before voltage evolution; thus the above mentioned phenomenon has less importance. But now, after a commutation which makes a given imbalance, a new imbalance occurs, corresponding to a static operation (closed/opened). This transient corresponds to a transient of the imbalance.

In the case of a parallel connection, this transient takes place after closing; and depends on the loop impedance between the parallel connected components, mainly inductive and resistive. Depending on wiring, the time constant is in the range of a few microseconds.

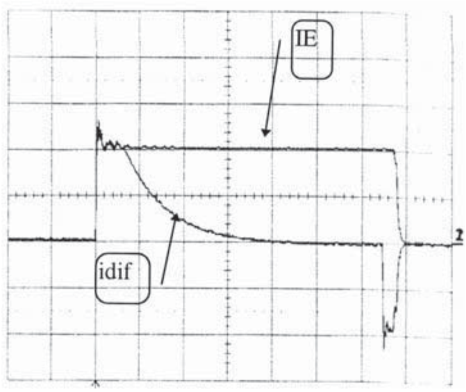


Figure 3.20. *Parallel connection of two IGBTs, with a large delay between drives. IE is the global current, Idif is the differential current IK1-IK2. Scales are: 10 A/div, 2 µs/div*

In the figure above we can notice full imbalance in favor of K1 during closing, and full imbalance in favor of K2 during opening.

3.3.5. *Technological parameters that influence imbalances*

A lot of important parameters influence the sharing constraints inside associations. These are mentioned according to their origins.

3.3.5.1. *Component [LAF 00]*

3.3.5.1.1. Internal parameters [LET 92]

Internal parameters are: V0, drive voltage of the grid circuit; R_G, resistance of the grid circuit; Vth, threshold voltage; tranconductance and input and output capacitances. As formerly mentioned, delays and commutation speeds hold great importance. Delays are mainly managed by charging the grid circuit up to the threshold voltage Vth. Thus, internal parameters are:

– non-linear value of input capacitance (Ciss);

– value of internal resistance of the component;

– value of the threshold voltage Vth (very sensitive to temperature).

3.3.5.1.2. About speeds

– During closing, current speed depends on transconductance and on the evolution speed of the grid to source voltage.

– During opening, voltage speed depends on the internal capacitances (Cgd – Miller capacitor-, Cds for MOSFET), and on external currents, power currents as control currents.

3.3.5.1.3. Temperature [RAE 96]

Most component parameters have a sensitivity to junction temperature. This creates a strong potential sensitivity to junction temperature imbalances of the components involved. In the case of a parallel connection, a cooler treatment is required in order to decrease the temperature differences between components: to obtain a strong coupling, the chips must be located on the same heatsink, within a short distance from each other. For a series connection, a single heat sink is generally not possible, due to the required electrical insulations, and due to parasitic capacitances: cooling technology will be adapted accordingly (for example oil may be used).

3.3.5.2. *Drive circuit*

General features are included to ensure as great a synchronization as possible, and the correct balancing of the drive currents. Options vary depending on the type of association, because the reference order of each element of the association is not the same for a series connection, although it is the same for a parallel connection. Inductance of the drive circuit is another dispersion factor causing imbalances.

3.3.5.3. *Power circuit*

The physical design of different associations of components leads to wiring between power connections (collectors, emitters, drains, sources, anodes, cathodes). Their impedances (inductances, capacitances, static and dynamic resistances) are the parameters influencing the internal balance. Once more, their relative importance depends on the kind of association, and on the operating phases.

3.4. Solutions for design

3.4.1. *Parallel association*

3.4.1.1. *Selection criteria for constitutive components selection [LAU 98]*

As we have seen, component association is highly dependent on the specific characteristics of each component, and more specifically on the dispersion of those characteristics. Here, we must distinguish MOS from IGBT. The former are only resistive (RDSon), with a positive temperature coefficient, which allows for self-balancing. In some areas, the latter have a negative apparent resistance temperature coefficient, so situations of conflict may occur, and a selection procedure may be required to limit internal imbalances.

The designer has two options:

– Selection of components; this prioritizes components from the same production batch. A further step is to associate components whose characteristics are nearby. The classic test, generally sufficient, sorts by classes of VCE voltage drops, at the current rating. As an indication, diodes should be within a VF(IN) characteristic in the range of 0.1 V, to reduce the static imbalance down to 15%. For IGBT, 0.15 V provides the same result. Figure 3.21 is an example of this selection at 25°C and shows its influence on the distribution of currents. An increase of temperature reduced the imbalance.

– "Derating" of the current capacity; depends on the number of elements involved. Usually, manufacturers provide some guidelines on this point.

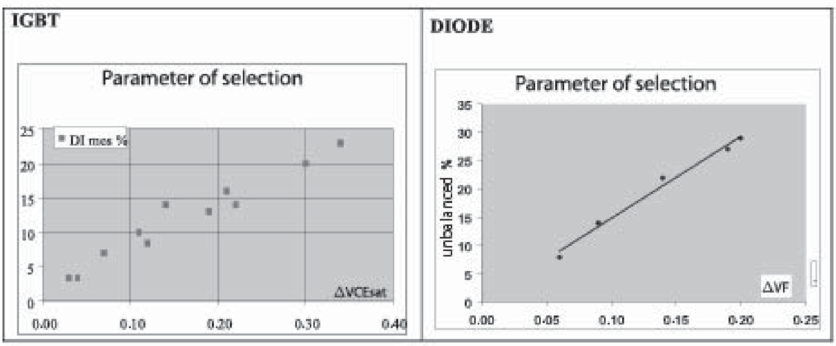


Figure 3.21. *Effect of selection on current imbalance*

3.4.1.2. *Grid drive circuit*

3.4.1.2.1. Grid circuit

The electric schematic for the grid command of one component is synthesized on Figure 3.22. The calculation is simple (second order). L_G is the parasitic wiring inductance.

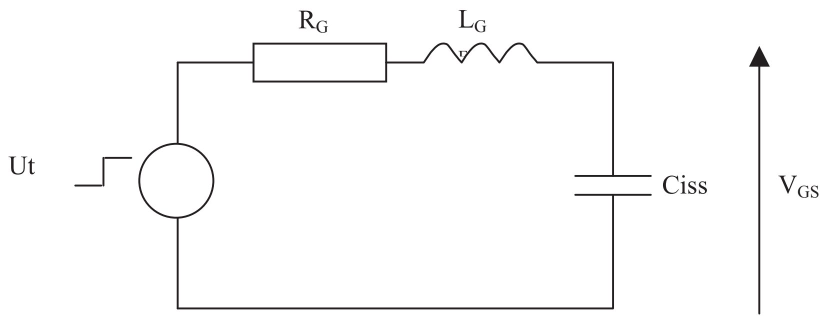


Figure 3.22. *Equivalent circuit for grid charge*

During switch-on, Ciss must be charged up to the threshold voltage, Vth. The circuit elements are:

– Ut, is a positive step; and

– Ciss, which may be approximated by Cgs, since Cgd is very low (large drain-source voltage).

During switch-off, Ciss must be discharged down to a voltage level close to the threshold voltage, Vth+Idrain/g (where g is transconductance). Here:

– Ut, is a negative step; and

– Ciss = Cgs + Cgd

Calculation of this second order circuit is simple, and determines the delay. The important parameters for charge and discharge are total grid resistance, and parasitic wiring inductance.

3.4.1.2.2. Influence of delay inside an association

For a parallel connection, with a unique command, a circuit may be synthesized as shown in Figure 3.23.

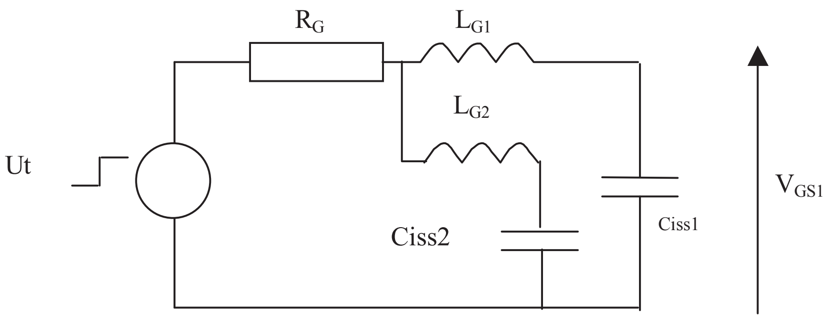


Figure 3.23. *Schematic of grid circuit for a parallel connection*

Difference of delays, the parameter which induces imbalances, depends, for a given Rg, on the difference ΔLg = Lg1-Lg2 between the two wiring inductances of the different grid circuits.

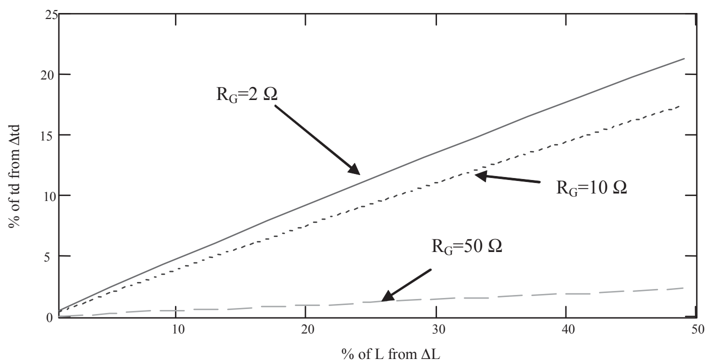


Figure 3.24. *Additional delay time due to a difference of grid inductance*

Figure 3.24 shows an increase of time when the grid inductance increases, for a given value of the grid resistance [JEAN 01]. Here, numerical calculations were done for various values of R_G (2 Ω, 10 Ω, 50 Ω), while L_G equals 50 nH as a basic value, and *Ciss* equals 1nF.

For large values of R_G (50 Ω), the variation of td is very small (as a relative value). This is about two times smaller than the value of L_G (a 20% deviation of L_G makes a 10% deviation of *td*).

3.4.1.2.3. Speed evaluation

– Closing: during the operation at threshold voltage, as a first order, current speed is proportional to grid current, i_{gth}. If the second order circuit is sufficiently damped (large R_G), i_{gth} is not influenced by the inductance. Thus, speed depends only on R_G. For low grid resistances, V_{th} is reached with a i_{gth} current defined by resonance. Then, speed depends also on the L_G value.

– Opening: during the operation at voltage level (V_{th}+Idrain/g), as a first order, voltage speed is proportional to grid current. Thus, speed depends mainly on R_G. Drain current also plays a role, via the drain source capacitance charge.

As a conclusion, important parameters for voltage speed commutation are (with decreasing importance):

– R_G and Cgd; then

– Idrain and Cds.

3.4.1.2.4. Technological solutions

A classic design, for parallel drives, includes a single command, making an initial synchronizm, associated with individual and identical grid resistances Rgi, for a better sharing of grid current. Usually, a common resistance R_G is added to control the global speed (Figure 3.25).

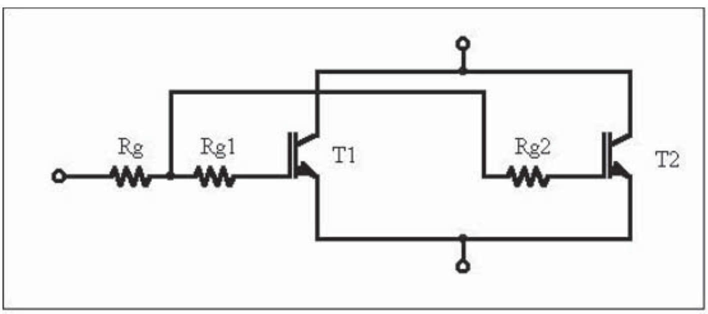


Figure 3.25. *Use of balance resistances Rgi (Rg1=Rg2)*

Additionally, these resistors prevent the high-frequency oscillation of paralleled components (the circuit consists of the two components, their internal parasitic capacitances and parasitic wiring inductances between grids, between drains and between sources; this is a high frequency oscillator, which must be strongly damped).

These resistors can also reduce the speed of commutation of the components, for the purpose of electromagnetic compatibility, or for control of switch-on speed at a tolerable level for the associated diode (powerful IGBT modules for example).

With regard to wiring inductors, remarks of the preceding paragraphs led to the use of low inductive wiring, and in particular the use of equal inductors.

3.4.1.2.5. Active balancing [HOF 99]

With very high power modules, with high costs, individual commands may be implemented for each module. In this case, a design may be implemented, with a command for each element, including sensing imbalance, in order to actively balance the currents (Figure 3.26).

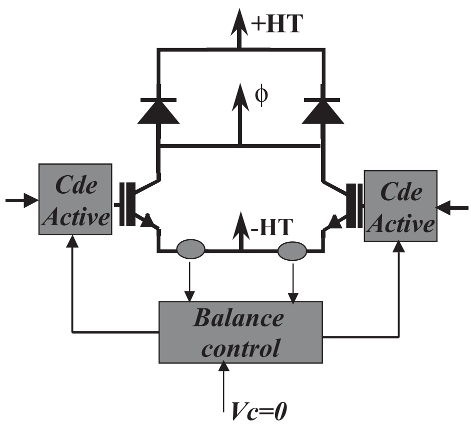


Figure 3.26. *Active control of current in two paralleled cells*

3.4.1.3. *Influence of wiring inductances on the power side*

3.4.1.3.1. Introduction

Connections between associated components are necessarily numerous, and must be properly designed in order to get the appropriate distribution of current between the elements. Connections show complex impedances (inductance, resistance and coupling).

Nowadays, power wiring is made using the busbar technology, which greatly reduces inductance. However, only a good design ensures the sharing of currents.

The main layout rules are as follows:

– for one switch, connections must be done on opposite faces. Such a design takes into account resistive and inductive issues, but not coupling issues;

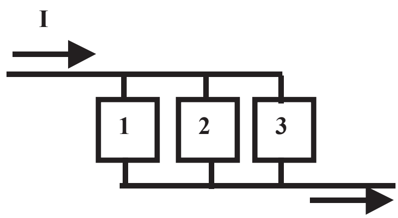


Figure 3.27. *Ladder disposition for a better current balance*

– there must be a minimal connection length in order to limit wiring inductances, which make overvoltages at switch-off. This requires a busbar between cells and decoupling capacitors;

Figure 3.28. *Use of busbar topology to reduce interconnection inductance (links high side switch H, low side switch L and DC bus capacitor)*

– individual connections with an important resistive influence must be well designed, with soldering or with screws, especially for high current rating modules.

3.4.1.3.2. Detailed analysis of the influence of wiring [JEA 01], [JEA 99]

In order to better understand the effects of coupling, a more accurate analysis of current sharing between several parallel components must include not only inductances and resistances, but also coupling between wiring inductances.

Figure 3.29 shows the model used in the case of paralleling two switches.

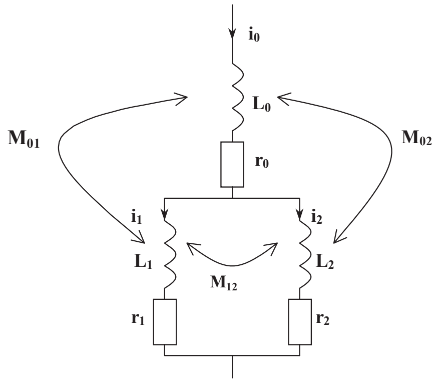


Figure 3.29. *Wiring model for evaluation of current imbalance between two parallel MOSFETs*

Detailed theoretical studies show [JEA 00] that the ratio between branch current and global current is:

$$\frac{i_1}{i_0} = \frac{r_2 + (L_2 + M_{02} - M_{01} - M_{12}) \cdot p}{r_1 + r_2 + (L_1 + L_2 - 2 \cdot M_{12}) \cdot p}$$

At low frequencies, the obvious condition of balance is: $r_1 = r_2$.

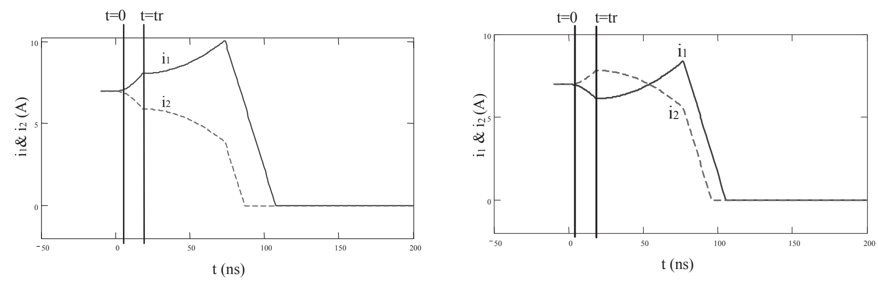
At high frequencies, the condition of balance is: $\frac{L_1 - L_2}{2} = M_{02} - M_{01}$.

The solutions are to comply with the former equation, or obtain a negative $|M_{12}|$ value as large as possible. The most favorable case is: $M_{12} = -\sqrt{L_1 \times L_2}$.

This shows that a symmetric structure, which is not possible to achieve in some cases [CLA 96], is not required in order to get identical currents i_1 and i_2. Only compliance with the above mentioned conditions is required:

– Switch-on: with up-to-date systems of components and wiring, in most cases, the drivable component defines its the switch-on speed, whilst parasitic inductances play a second order role. However, for components that do not control their speed (like diodes, or thyristors, etc.), current sharing is directly dependent on wiring inductances, and on their coupling.

– Switch-off: section 3.6 mentioned additional possible imbalances of the current, due to the differences of voltage commutation speeds (loop currents). A design rule is – in addition to obtaining equal voltage speeds – to try to design in order to get the component with the largest dV/dt to be the most delayed. This is illustrated in Figure 3.30.

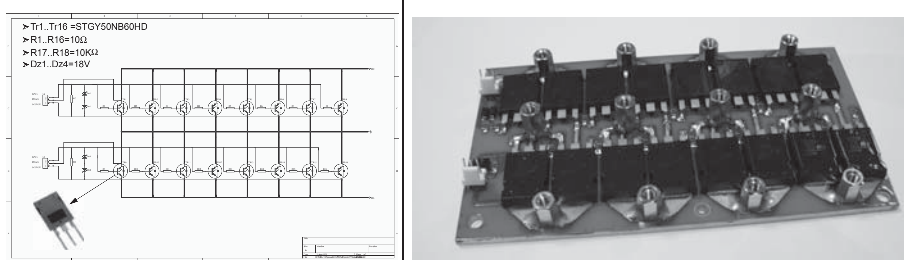


(a) (b)

Figure 3.30. *Opening*

3.4.1.4. *Design examples*

Figure 3.31 shows the design of a 400 A, 600 V module by paralleling the height of plastic packages, standard TO 247, for each commutation function, on SMI support. Components are selected according to proposed criteria [LAF 01].



Schematic of the module | Design

Figure 3.31. *400 A module by paralleling height components*

3.4.2. *Series associations [LAU 00b]*

On one hand, semiconductors are more sensitive to voltage overloads than to current overloads. On the other hand, series connection makes voltage imbalances. While voltage evolution speed is much faster than current evolution speed (10 kV/µs compared to 1 kA/µs), the importance of a delay on one component compared to another is much more important in series than in the case of parallel connection.

3.4.2.1. *Selection of components*

The semiconductor parameters that influence delays and commutation speeds were previously mentioned for parallel connection, and remain the same.

Two solutions available are:

– selection of components (same batch, same wafer); and

– choice of robust components against avalanche.

3.4.2.2. *Grid drive circuit*

In series associations of components, parallel or matrix, components must commutate in the most synchronous way, in order to reduce differences in the sharing of electric constraints. There are two origins for the delays possible between commutations: one is from dispersion of the internal characteristics of components; the other is from external causes, including dispersion of orders of commutation delivered by the drive circuits.

For series connection of switches, the most frequently used drives are:

– cascade commands;

– optical commands;

– commands by transformers.

3.4.2.2.1. Cascade commands

These commands use the commutation of the lower switch in order to generate the commutation of the superior switch, by means of the capacitor. A delay occurs between commutations of the different switches of the series connection, and thus a lack of synchronization by principle. This has to be taken into account for the voltage definition of switches. In practice, cascade commands are usually used for series connection of switches, but for no more than three or five elements.

3.4.2.2.2. Optical commands

These commands only transmit the drive signal and require an additional source of energy. For low switching frequencies, this energy may be obtained from the power connections of the switches to be driven. A very important feature is the great sensitivity of optical receivers to perturbations. This is well known for photo-couplers; this is also the case for optic fibers. The optic fiber itself is not sensitive to electromagnetic perturbations, but the optical receiver at the end of the fiber is extremely sensitive. For a series connection operating with large dV/dt, the optical receiver and its proximity command must be implemented inside a local faraday cage, connected to the voltage of the switch to be driven.

For example, very high voltage converters, connected to the grid, and operating at relatively low frequencies, are designed this way. In this case, the association of the optic with the self-supply of drive boards is a good technological solution.

3.4.2.2.3. Transformers

The strong advantage of transformers is the ability to deliver together the drive order and the required energy. We must pay attention, on one hand, to the strength on the voltage insulation which supports the dV/dt and, on the other hand, to the parasitic capacitance of the transformer.

For fast high voltage applications, a classic drive is made of a pulse transformer, whose primary is made of a high voltage cable passing through a ferrite tore (which is indeed the magnetic core), and whose secondary is made of a few turns of wire, with low voltage insulation, wound around the core. The primary of this transformer is thus made of only one turn. The ferrite core must be connected to the switch to be driven. This kind of transformer has very good performances, and is well suited for industrial applications. Drive pulses transmitted by the transformer are used directly, or memorized, according to the drive requested by the switch.

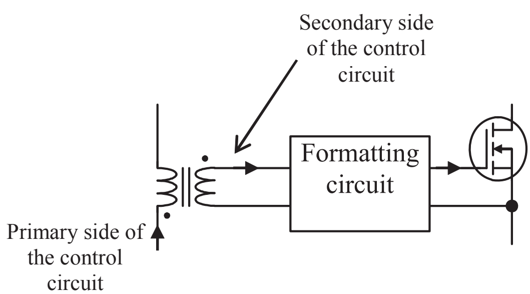


Figure 3.32. *Drive by pulse transformer, which ensures the galvanic insulation*

Synchronization between stages may be achieved by series connection of the primaries of these transformers, which in this design have the same current flow, supplied by the drive circuit. This way, all the stages of the series connection have the same current.

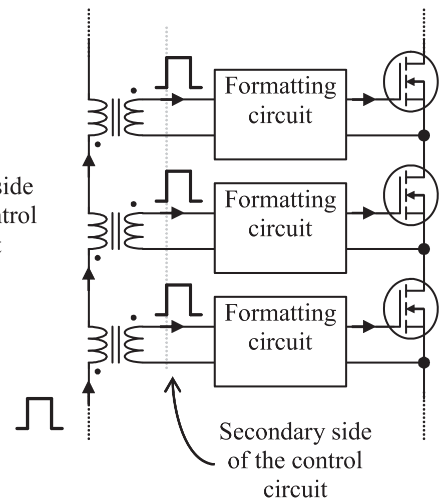


Figure 3.33. *Synchronized command of stages by series connection of the drive circuit primaries*

The ferrite core does not need insulation, but requires a connection to the voltage of each stage. When commutation dV/dt occurs, capacitive currents between commutating components and the primary cable must not flow through the proximity drives of the components, but instead must flow throughout this voltage connection.

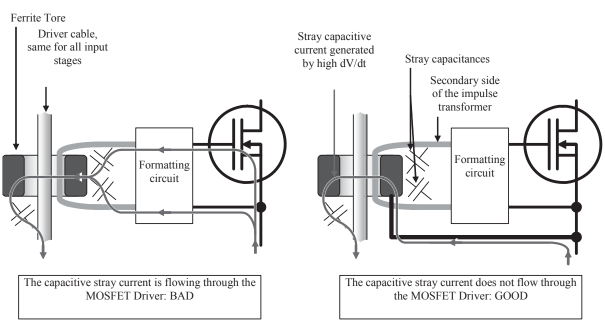


Figure 3.34. *Voltage connection of the core, which allows the circulation of parasitic capacitive currents during dV/dt*

The central hole of the core must be large enough to allow sufficient space for a drive cable of large diameter. Indeed, the voltage strength between the command and the power is permitted by a high voltage drive cable.

The drive cable is mounted in parallel position along the power board, for its entire length. To avoid inductive coupling with the power circuit, which could generate a parasitic current during power dI/dt, the return pass of the drive cable is mounted close to the ferrite core. This way, mutual inductance between drive and power is reduced.

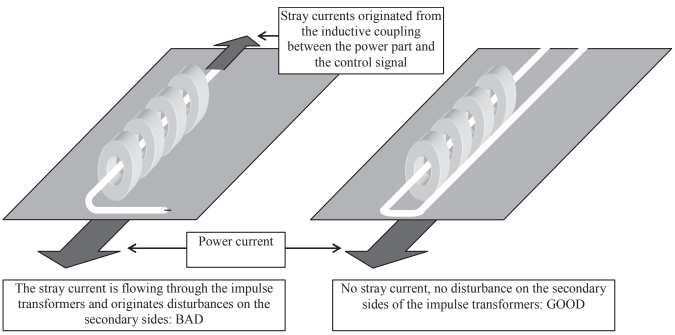


Figure 3.35. *Mounting of the drive cable: the way and the return pass are close together in order to reduce the mutual inductance between the drive circuit and power circuit*

3.4.2.3. *Importance of parasitic capacitors*

With series connection, high levels of voltage are reached, this leads to specific constraints on interconnections of the converters elements. The following text gives some indication of the issues related to high voltage:

– A filer wiring exhibits a linear inductance of about one microHenry per meter, and a linear capacitance of about one hundred microfarad per meter.

– In classic applications of power electronics, with low voltages, engineers are facing parasitic inductances of the wiring. In order to reduce these inductances, classic solutions lead to use of large conductors, with a return pass as close as possible to the way paths; see [JEA 01], in particular the chapter on wiring models.

– When there are high voltages, for the same commutated power, currents and dI/dt are much smaller, and issues with wiring are related to parasitic capacitors. This means an important part of the switched current is used to charge parasitic capacitors, and does not participate in the energy transfer.

On the other hand, physics does not allow for the creation of high voltage wiring with very low capacitances. It is possible to make very low inductance wiring with very large conductors, with conductors close together for the way and return currents. However, a wiring with very low capacitance would correspond to wires very far away from each other, with a very thin section. In this case, the electric field in the air or in the insulating layer has exceeded the maximal allowable field, and partial discharges occur around the cable.

In conclusion, very low inductive wiring may be achieved, but it is impossible to create very low capacitive wiring, at least with high voltage.

For a series connection, series connected elements show parasitic capacitances with external parts: for instance with mechanical mounting; and with command. When components under voltage are closing, the discharge of these capacitors, through the series connected elements, leads to a change in the current shared between these components. Figure 3.36 shows the series connection of switches and the influence of the environment on parasitic capacitors, and current sharing between these switches.

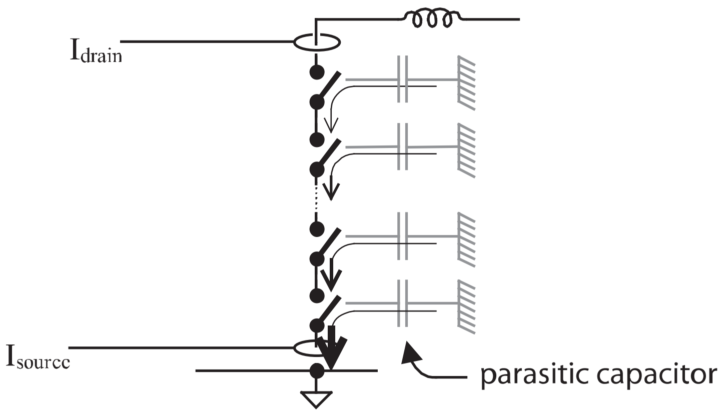


Figure 3.36. *Series connection and the influence of parasitic capacitor current sharing*

The “hot points” of a switch refers to the parts of this switch stressed by a voltage change compared to ground. In turn the “cold points” of a switch are the parts of this switch that have a constant voltage compared to ground, and therefore are not stressed by a dV/dt compared to the ground and environment.

Thus, components connected to a cold point are stressed by a current overload. The following curve, from [GUI 95], shows currents at a hot point (drain of a superior MOS in the series connection), and currents at a cold point (source of the ground connected MOS), in a series connection of 40 MOSFET, supplied under 10,000 V, and flowed by a nominal current of 1.6 A.

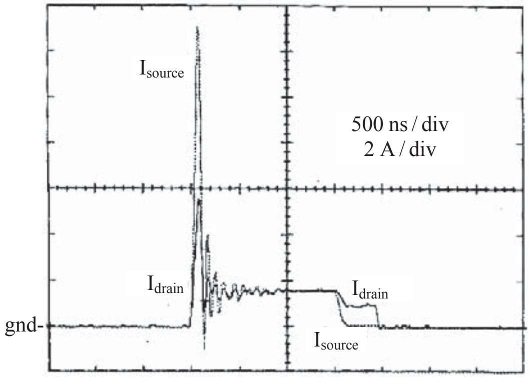


Figure 3.37. *Waveforms of currents sharing at switch-off in a 40 MOSFET series connection*

During commutation, the current imbalance of 10 A may be compared to the nominal current of 1.6 A. These current imbalances come from the discharge currents of the parasitic capacitances of the switch.

During commutations of a matrix, between stages and mechanical grounds, parasitic capacitors generate currents during the dV/dt. Parasitic capacitors of the stages stressed by the highest dV/dt compared to external parts must be reduced in order to reduce over-currents. Where distance increases from the ground, and where successive stages make electrostatic screens from one to the next, structures in the orthogonal direction, are well suited, compared to structures utilizing small distances from the ground plan.

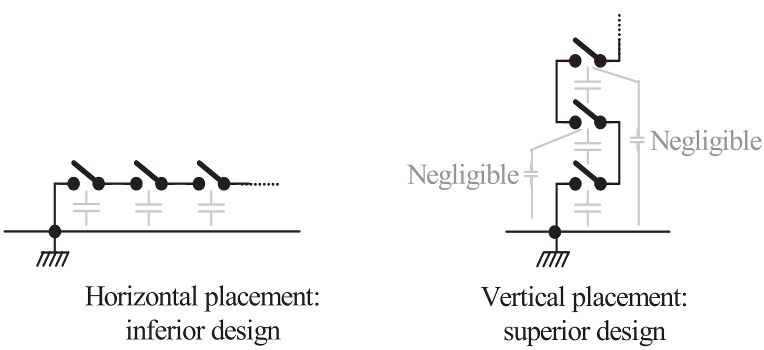


Figure 3.38. *Series connection: vertical implementation of elements, in order to reduce dV/dt applied to parasitic capacitors during commutations*

With an horizontal implementation, all parasitic capacitors are in the same range of magnitude, but dV/dt increases in the region of the hot point. Thus giving parasitic capacitive currents more importance.

With a vertical implementation, the screen effect made by the lower stage minimizes the parasitic capacitor with the mechanical ground, this, can be compared with the capacitor of the inferior stage. All dV/dt are thus of the same order of magnitude (the magnitude of the commutation of a stage) and parasitic currents flowing through parasitic capacitors and components are reduced.

For series connection, vertical implementation of the elements under voltage is well suited, in order for the low voltage stages to take advantage of the screen effect of the high voltage stages. The dV/dt seen by parasitic capacitors are those of only one stage. The influence of parasitic capacitors compared to the mechanical parts and the environment is minimized.

3.4.2.3.1. Soft commutations

Resonant circuits may be designed, so that parasitic capacitors are integrated into resonant capacitors [LAP 98]. This way, parasitic capacitor energy is not wasted during commutations. This allows for the design of high voltage converters with very good efficiencies that are able to operate at higher frequencies.

3.4.2.4. *Voltage management*

As components are sensitive to the power voltage, it is necessary to design protection circuits, and perhaps balancing circuits. Some strategies for this are presented in the following sections.

3.4.2.4.1. Voltage balance

In a series connection, we must take care not to apply a voltage to components that they are unable to support. Assuming this feature, in addition to very well synchronized commands, a traditional solution was to obtain every time an equal balance of voltages at any given time. For this reason, components are connected in parallel with a resistor for static balance (flowed by a current ten times larger than the leakage current of the switches, or ten times larger than the maximum deviation of the leakage currents of the switches), with a RC circuit for commutation help (which minimizes the imbalances during switch-off of the components), and maybe with a clamping circuit in order to limit the maximum voltage [FRE 01]. This is a very heavy solution, due to the number of additional components, and their cooling constraints. Nevertheless, this is the well suited solution if the safe operating area for the components is reduced. The equal balance may also be achieved by a command including a closed loop control for active balancing.

3.4.2.4.2. Clamping of voltages

Voltage balance is not always a strict requirement. An alternative strategy does not look for balance at any cost. Rather, the minimal requirement is to operate the switches of the series connection inside their safe operating area. Nowadays, as components of power electronics have vastly extended safe operating areas, series connection of these components may be achieved with a clamping device on each stage, or even with no additional protection if the components are able to support intrinsic clamping by the avalanche.

They are three types of voltage limitations for semiconductors components:

– Use of the possible ability of protection against voltage, appropriate for the component to be protected. This is an *intrinsic clamping* of the component (by the avalanche). One must pay attention to the word avalanche, as it may be understood not only as clamping, but also as destruction of the device.

– Protection by an added device, implemented in parallel on the component to be protected. This kind of protection is traditionally called *passive clamping*.

– Action on the drive electrode of the component to be protected when a given voltage is exceeded. In linear operation, the component regulates the voltage across its connections. This is called *active clamping*.

3.4.2.4.3. Intrinsic clamping

The intrinsic clamping ability is well known for components such as transils and Zener diodes. Other components such as diodes, MOS and IGBTs may include manufacturing quality that can confer to them, in addition to a very good reproducibility of their characteristics, a good ability for clamping. Nowadays, few devices are specified to support a clamping intrinsic avalanche. For MOS transistors, a classic specification is a tolerance of their direct forward current rating as an avalanche clamping current. This specification of a current is well suited for power electronics. For some components, an energy is specified, corresponding to tests under a low current over a long period of time. This specification does not inform the designer of the behavior of the component when it is brought to clamp during a switch-off commutation. When using the clamping avalanche of the component, it is necessary to compare the current to be clamped in the worst case to the clamping current tolerable by the component.

In the case of diodes, the worst case current is difficult to determine. A good selection criteria of diode technologies is the ability to support their nominal current as an avalanche current. In this case, these diodes are used in a series connection or matrix connection without any unitary selection. Conversely, as long as the manufacturer does not specify the avalanche current rating of the diodes, any change may occur in the characteristics, due to a change of the diode.

For example, here is a comparison on avalanche clamping tests between two generations of 500 V MOS: IRF840 and IRFB11N50A. The latter being a last generation transistor.

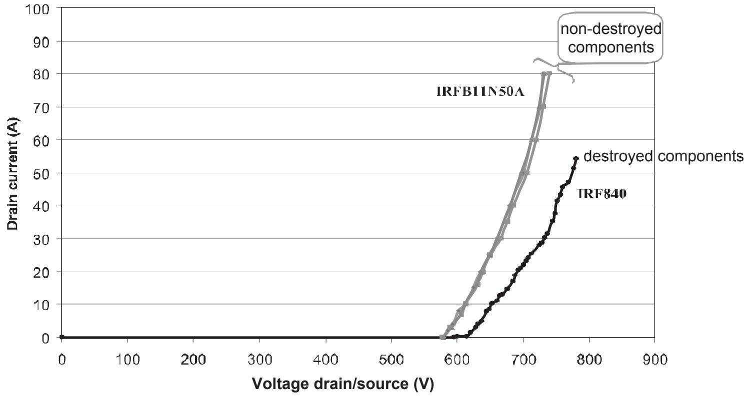


Figure 3.39. *Dynamic characteristics of two types of 500 V MOS during avalanche condition*

IRF840 is destroyed for an avalanche current of 60 Amps, while the IRFB11N50A component operates with a 80 Amps current. Additionally, during avalanche operation, the dynamic resistance is smaller for the IRFB11N50A component, and this allows the voltage across the component to remain smaller for the same current.

Manufacturers guarantee an avalanche current of 8 A and 11 A respectively, in other words the specified nominal current.

3.4.2.4.4. Passive clamping

Specific components are used for passive voltage protection, as transils or varistances, connected in parallel to the semiconductors to be protected. This kind of protection requires a clamping voltage, for the protector component, lower than the avalanche voltage of the component to be protected (e.g. a 440 V transil for a 500 V MOS). Figure 3.24 gives the voltage characteristics of transils 1.5KE 350 and 1.5KE 440 Volts.

The dynamic resistance of protection systems leads to an increase of the voltage across the protection component, the clamping current increases. It may reach the maximum voltage rating of the component to be protected, which then clamps or is destroyed (according to its ability to support the clamping by avalanche).

In order to obtain a voltage lower than the voltage rating of the MOS, three classic solutions are used:

– Choice of a transil with a lower voltage rating. Drawback is "derating" of the voltage rating of the protected components. For example, the 500 V MOS must be used under 350 V.

– Series connection of transils with lower ratings (which have a lower dynamic resistance).

– Parallel connection of several transils. This way, dynamic resistance is reduced by the same factor as the number of associated diodes. Dynamic resistance ensures a good balance of current between diodes. Drawback is the cost of this method, and its volume.

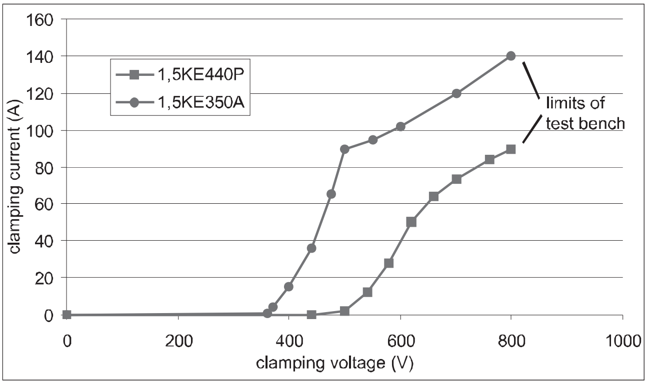


Figure 3.40. *Dynamic characteristics of 1,5KE350 and 1,5KE440 transils, during clamping operation, at a very high current*

3.4.2.4.5. Active clamping

Active voltage protection of driveable semiconductor components is achieved via feedback, on the command electrode, from the protected component. The operating mode of such a protection against overvoltage is similar to that of a closed loop voltage control [LAU 99].

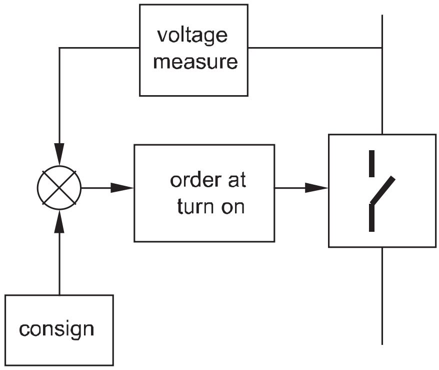


Figure 3.41. *Active voltage protection: closed loop voltage control*

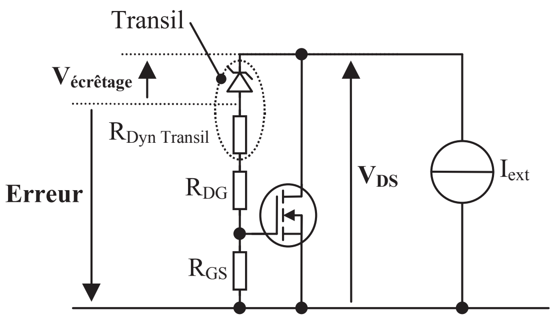


Figure 3.42. *Basic schematic of a MOS, protected by active clamping*

The apparent resistance of the clamping circuit may be a very low benefit from the loop gain. As the component is used inside its safe operating area, it may be used at high current and absorb high energies. This way, active voltage clamping protection of semiconductor components appears to be an efficient and robust solution (very low dynamic resistance, very high current rating).

Now, as for any classic closed loop control, a large gain may lead to instabilities of the control. This occurs for operation at low power current, and with low drain-grid resistance (R_{DG}), as seen in the following example.

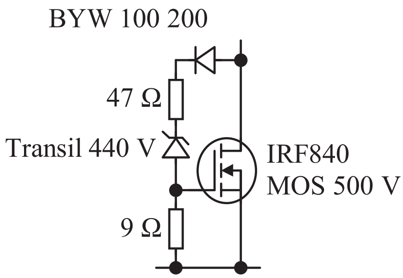


Figure 3.43. *Test circuit for the study of closed loop voltage control instabilities, at low current*

For parallel and series connections, the design of the closed loop control must take into account oscillatory modes between components.

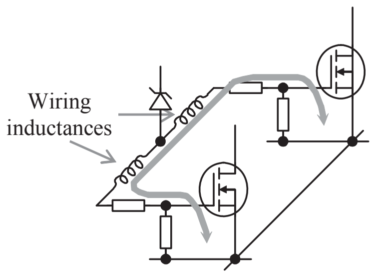


Figure 3.44. *Instabilities due to exchange of charges between grids of parallel connected components*

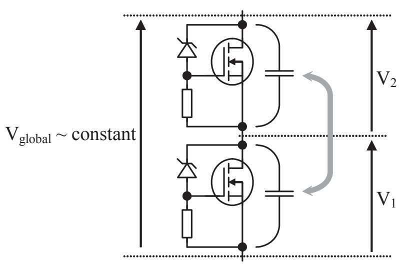


Figure 3.45. *Instabilities due to exchanges of charge between drain-source capacitances of series connected components, during operation under a defined exterior voltage*

Active voltage clamping protection of semiconductor components appears as an efficient and reliable solution, which makes a very low dynamic resistance and very high current rating. On the other hand, stability of the closed loop control must be achieved. This stability is more difficult to achieve when component commutations are faster, and when load variations from the exterior are stronger.

3.4.2.5. *Reliability of series connections* [LAU 00a]

Series connection of components may be used to make a switch with very high reliability [CHA 00]. Indeed, the first consequence of the failure of a component is the components inability to support a voltage. Thus, a parallel connection of components is less reliable than a single component. Only one failing component is necessary to cause failure of the global switch. Repairing requires isolation of the failing component.

With a series connection of components, failure of one component may be tolerated. If the series connection includes a sufficient number of components, a voltage security margin of some stages allows a tolerance of the corresponding number of failing components. For this, other components have to share the voltage between them; and command must not be interrupted by the failing component. In a practical sense, the failing component is always conductive, and does not disturb the good operation of the switch.

With series connection, reliability is improved. The global switch is more reliable than the stages it is made of. Moreover, the system is no longer in danger of a random failure. A random failure may appear, but it will not put the switch into default. The series connection offers a possibility of natural redundancy that allows a certain tolerance of failure improves reliability and allows for a possible preventive maintenance. For example, a preventive control may be run every three years to verify the presence or absence of defects on stages, and the correction of these defects.

Similarly, matrices may be tolerant to failure if all components continue to be controlled despite the failing component, and if the design of the matrix is planned accordingly. Thus, the 25 kV – 1,600 A switch presented at the end of this chapter should have a 20,000 hours MTBF, if failure of one component would lead to failure of the switch. Actually, following the tolerance of failure provided by the series connection, it offers a lifetime of 200,000 hours if there is no preventive maintenance. With a preventive maintenance, it enables us to perform an availability rate of 99.99%. In actual fact, the switch is more reliable than the command board that drives it.

3.4.2.6. *Design: Specific features of high voltages*

3.4.2.6.1. Perturbation aspects

As voltages are added along the series connection of switches, the dV/dt, compared to the environment, from the top (hot) point of the switch, may become very important. From a circuit point of view, we can say that this dV/dt generates currents in all parasitic capacitances with the surrounding elements. From an EMC view point, we have a generator of electric field in the air. Although levels change (20 kV switching within 20 ns matches 1MV/µs), design rules relating to EMC are the same in high voltage as in classic power electronics. If necessary, Faraday cages, made judiciously, can provide very effective solutions. The signals and power supplies may be distributed by common mode inductors, in order to avoid perturbations from high frequency voltages, on the so-called "cold" points, during commutations.

3.4.2.6.2. Security area at switch-on and security area at switch-off

The minimal requirement to comply with, in a series connection or a matrix connection, is to maintain the components in their areas of security. As a matter of fact, the high voltage switches, operating in thyristor mode (ZCS), are much easier to achieve than those operating in dual-thyristor mode, or hard commutation. There are two physical reasons for this:

– Firstly, for most of the components, the security area for switch-on is larger than the security area for switch-off. This phenomenon is already well known for bipolar transistors. It is possible to make an excellent synchronization at switch-on by strong command currents. For example, with a three amperes current trigger on thyristors packaged in TO220 cases, voltage on the component terminals drops within 50 ns [CHA 01].

– Wiring inductances help commutation. That is why the voltage drop is used as a criterion in the case of a strong switch-on of the component (MOS, thyristor). This switch-on is so fast that all the voltage is applied to the terminals of the wiring inductances: this last reason defines the dI/dt.

3.4.2.6.3. Partial discharges and the Paschen curve

The Paschen curve is a bathtub shaped curve, which reflects the voltage strength of a gas blade, as a function of its pressure. For normal pressure or higher pressures, the voltage strength increases between the two parts, by enlarging the distance between the parts, or increasing the gas pressure. In the first case, the electric field decreases. In the second case, the average trail of ions and electrons is reduced, and therefore the trip, during which they will be accelerated by the electric field. With a low pressure below the millibar, the voltage strength increases by reducing the distance between parts. In this case, ion or electron will have little probability of hitting a molecule before reaching the attracting electrode. This way, gas pipes hold 20 or 30 kV with a distance of a few millimeters between electrodes. Thus, there is a minimum Paschen voltage, below which the dielectric breakdown can not occur, regardless of the distance between parts: this minimum is around 300 volts in the air.

Let us now consider the breakdown voltage at the interface between two different dielectrics. Consider two electrodes, isolated from each other by two superimposed dielectrics: the equivalent schematic seen by the electrodes is a series connection of two capacitors, in parallel with two resistors. Under a continuous voltage, voltage sharing involves the resistivity of the areas. For example, in the case of a solid polymer type insulator superimposed on an air space, we can observe that the solid dielectric holds most of the voltage, due to its very high resistivity. With alternative or pulsed signals, the voltage sharing involves the inverse values of capacitances. The main voltage appears on the terminals of the smaller capacitor. In the case described above, the electric field is now mainly in the air. Also, the material has a high permittivity, the electric field is weak inside it, and the field is important in the air. When the maximum field in the air is exceeded, there are egrets that correspond to a micro-arc, which discharges the capacitor made of the air space and the local charge of the insulating layer. This is not a complete short circuit, as the solid insulator is not destroyed. This phenomenon is called a partial discharge. If the insulator is a polymer, partial discharge punctures it gradually. Mineral insulators are stronger against this phenomenon. In 50 Hz high voltage transformers, the phenomenon of partial discharges is measured by the high frequency noise generated. This physical phenomenon is also used industrially to generate ozone.

With pulsed or alternative high voltage, we obtain a better insulation using air alone, rather than by adding an intermediate insulator, which increases the field in the air and causes partial discharges. Otherwise, it is better to use materials that have weak permittivities, such as Teflon. Every dielectric casting between two parts must be free of air bubbles, under penalty of partial discharge in the bubble, and then gradual degradation of the insulation.

Because of the above-mentioned Paschen law, there are no partial discharge problems for conventional power electronic voltages, i.e. below 1,000 volts. However, for study of higher voltage systems, these physical phenomena impose different design rules.

In power supplies, while the voltage does not exceed the minimum of Paschen, transformers do not mandatorily require vacuum impregnation. Now, partial discharges appear and are heard when the power supply runs an alternative dielectric test. This explains the questions raised by supply manufacturers between continuous or alternative power supply dielectric test results. As mentioned above, the physics of these two tests is not the same. With alternative voltage, the test degrades the transformer by partial discharges, resulting in a limited duration of the test. The shape of parts is important for the electric field in the air around these parts. An edge makes a strengthening of the local electric field, and a partial discharge may occur at that point.

For high voltages, liquid insulators such as mineral oils are still commonly used. These are high-performance solutions in terms of dielectrics and cooling. Mineral oil is a very good dielectric. As a liquid, it tolerates partial discharges by the edge effect, due to the renewal of oil at the point of strong electric field. No air bubbles can be created, and residual bubbles are naturally removed, by gravity or by filling oil under vacuum conditions if air bubbles can be blocked, as in a transformer. A circulation of cooling oil may be used and allows a very efficient cooling, as with all liquid cooling systems.

3.4.2.6.4. Design examples

Figure 3.46 depicts a MOS board for 5,000 V, 1,000 A, driveable at switch-on (thyristor mode), and a 25 kV 1600 A module allowing for a voltage drop within 20 ns and a lifetime of 200,000 hours.

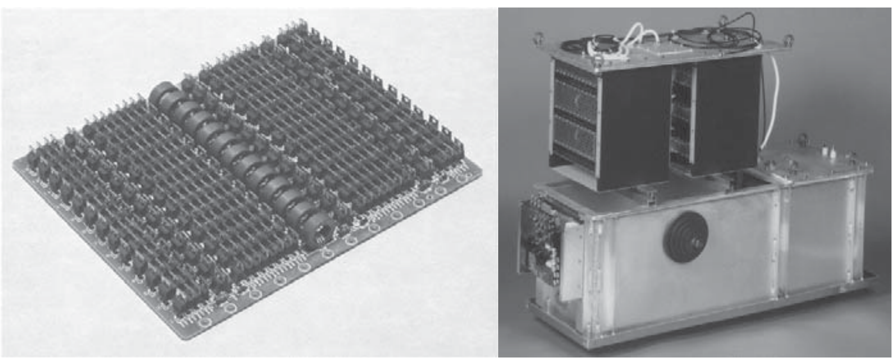


Figure 3.46. *MOS board and module*

Figure 3.47 is a 5,000 V 500 A board driveable at switch-on and switch-off, holding short circuits without any additional series inductance, and able to open under short circuit.

Figure 3.47. *Board of MOS ON OFF CC, 5 ,000 V, 500 A*

These boards are used for the generation of square power waveforms with strong front edges (+30 kV and -30 kV maximum, with 500 A, within 100 ns), able to support perfectly arcing short circuits (no dI/dt limitation by additional inductance [CHA 00]).

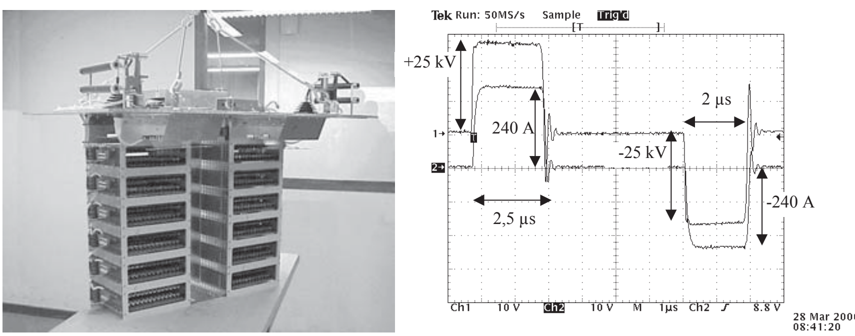
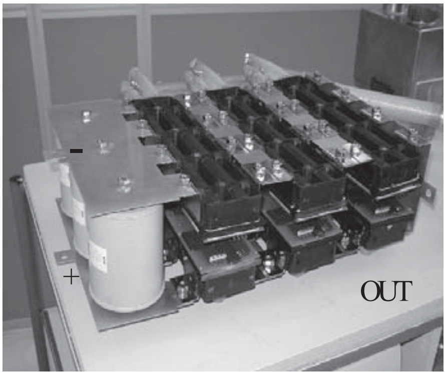


Figure 3.48. *Half bridge made of two 60 kV switches, and output signals*

A further design example is the IGBT inverter: 5,000 V 400 Amps (ALSTOM – European contract HIPO) [FRE 01].

This is a high power inverter for traction application, including modules with high current and voltage ratings (3,300 V 400 A in the example shown, 6,500 V in the final application). The series connection is thus reduced to a smaller number of more expensive items, which clearly prohibits redundancy. It is therefore vital to ensure not only protection but also voltage balance in the association. A specific control board was developed and integrated into the modules, allowing this dual function of balancing and protection.



Electrical Properties :

5.5kV DC Bus

Output : 4kAC-300Arms
Power : 700kW
Size : 500 X 350 x 160 mm

Weight : 15kg

Figure 3.49. *Traction inverter (ALSTOM-HIPO). Electrical properties: 5.5 kV DC Bus; 4 kAC-300 A output; 700 kW power; 500x350x160 mm size; and 15 kg weight*

A board of diodes, another example, is depicted below in Figure 3.50. This matrix of diodes does not use any balancing system, and components are not selected. The diodes involved support their nominal current as an avalanche current.

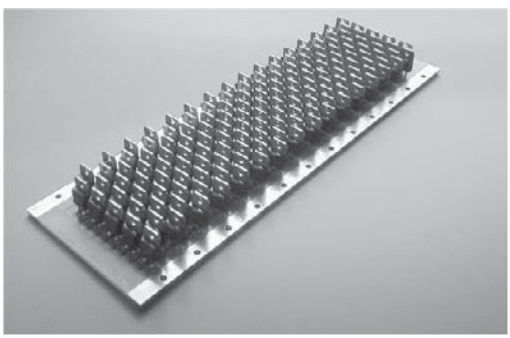


Figure 3.50. *Diode board: 12 kV, 800 A peak, made of a matrix, 10 series - 16 parallel*

The final example is a thyristor board. To meet the needs of commutation of high pulsed currents during large times (several dozen microseconds), a board made of thyristors was developed. It is made of a matrix including five components in series, and ten in parallel.

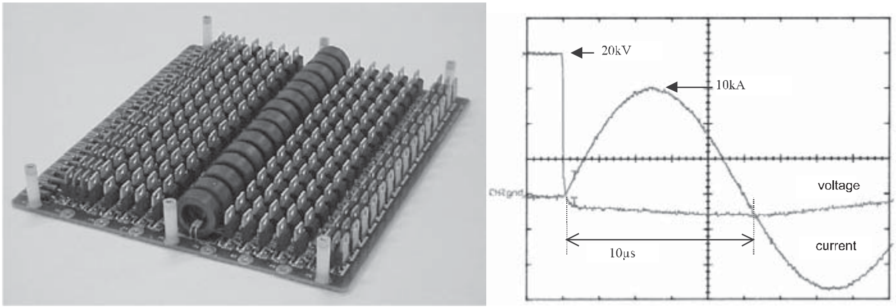


Figure 3.51. *Thyristors board and commutation under 20 kV with two series connected boards*

Synchronization is made by a strong gate current to reduce spreading at switch-on. The curves in Figure 3.51 show a commutation of a 20 KV module, made of two series connected boards, on a RLC circuit. There is a voltage drop of 20 kV within 20 ns, so dV/dt = 1 MV/µs; and an increase of current from zero, dI/dt = 12 kA/µs.

3.4.3. *Matrix connection of components [CHA 99]*

Series connection is an association which may be defined as follows:

"Series connection of components is a kind of association where, during static operation, all components flow by the same current, and where the global voltage is shared between them" [LAU 00a].

In turn, parallel connection may be defined as follows:

"Parallel connection of components is a kind of association where, during static operation, all components are under an equal voltage, and where they share the global current between them" [LAU 00a].

In the case of high voltage and high current components, the number of associated components may be high. The components may be series connected to support a high voltage, and these series may then be associated in parallel. We call this association *a parallel connection of series associations.*

Components may be parallel connected to commutate important currents, and these parallel connections may then be associated in series. We call this association *a series connection of parallel associations.*

Figure 3.52 illustrates these two associations for diodes.

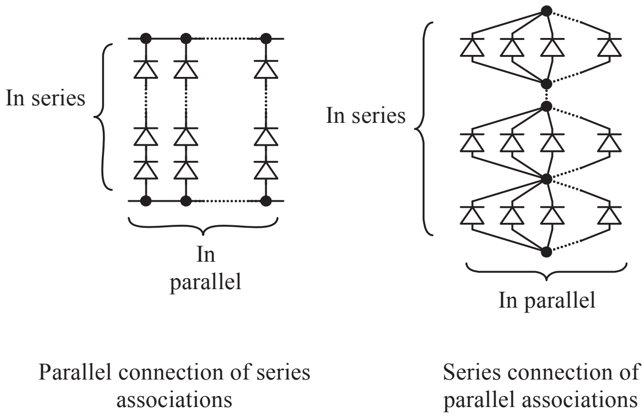


Figure 3.52. *Parallel connection of series associations and series connection of parallel associations*

It should be noted that a series connection of large power IGBT modules (for instance for traction) is, as a matter of fact, a series association of parallel connections; because any IGBT power module is usually made of a parallel connection of several dies of IGBT and diodes.

Let us call the structure of Figure 3.53 a matrix, which shows both the series connection of components and the parallel connection of the same components.

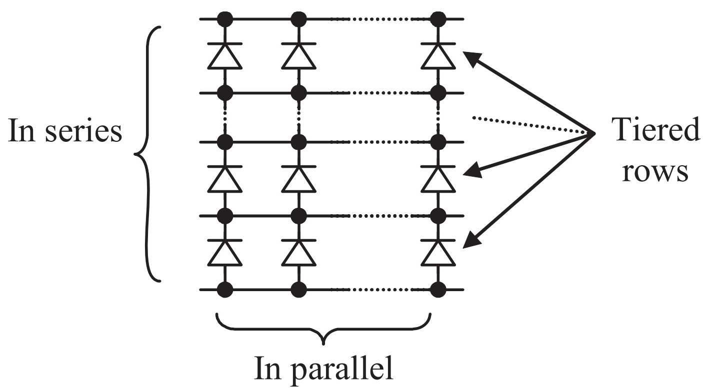


Figure 3.53. *Matrix*

The matrix is different from the series connection of parallel connection because the current of each stage is not flowing to a single point. In practice, this leads to the design of switches with very low parasitic inductances, since the current remains distributed over the entire width, in other words, between the paralleled components. When there is no current concentration, switch inductance remains minimal.

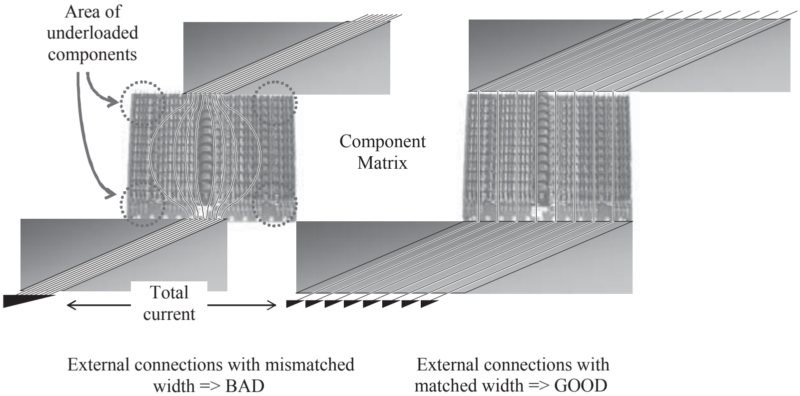


Figure 3.54. *Recommendations for external connections of the component matrix*

Nevertheless, connection impedances between components, still physically present, make the matrix more complex. The matrix includes two dimensions, series and parallel, and it is impossible to determine the kind of association (series or parallel) which was at the foundation of the structure. Figure 3.55 shows the general matrix.

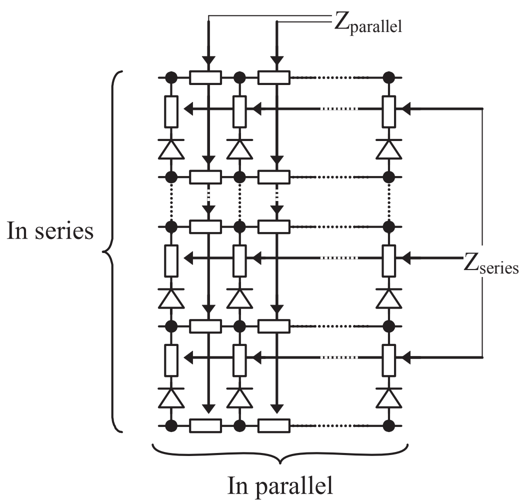


Figure 3.55. *Matrix schematic including parasitic wiring inductances*

Impedances Z_{series} and $Z_{parallel}$ between stages and between lines are part of the matrix. In practice, these impedances represent the matrix component connections. Resistive or inductive, these series impedances (Z_{series}) modify current and voltage levels seen by components, and the parallel impedances ($Z_{parallel}$) suppress the equal voltage concept between the different stages of the matrix. Additionally, couplings of mutual inductances may occur.

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