Investigation of PWM-controlled MOSFET with inductive load

Examensarbete utfört i systemteknik
vid Linköpings tekniska högskola
av
Tobias Ljunggren

LiTH-ISY-EX-ET-0233-2002

Handledare: Peter Grundberg, Volvo Powertrain
Examinator: Jonny Lindgren
Linköping 2002-06-12

Avdelning, Institution
Division, Department

Institutionen för Systemteknik
581 83 LINKÖPING

Datum
Date
2002-06-12

Språk
Language
Svenska/Swedish
X Engelska/English

Rapporttyp
Report category
Licentiatavhandling
X Examensarbete
C-uppsats
D-uppsats
Övrig rapport
____

ISBN

ISRN LITH-ISY-EX-ET-0233-2002

Serietitel och serienummer
Title of series, numbering

ISSN

URL för elektronisk version
http://www.ep.liu.se/exjobb/isy/2002/233/

Titel
Title
Investigation of PWM-controlled MOSFET with inductive load

Författare
Author
Tobias Ljunggren

Sammanfattning
Abstract

This report is the basis for a Bachelor of Science thesis in engineering done at Volvo Powertrain in Gothenburg.

The problem consisted of investigating a circuit with a PWM-controlled MOSFET driving a DC-motor. The problem was to investigate what caused the circuit to break the transistor. Finally an improvement of the circuit is designed making the MOSFET withstand the stressful conditions exposed to.

An overall description of the problems with switching an inductive load using a MOSFET as switch is done. Some methods to protect the MOSFET from failure are also discussed. Finally a discussion is held to suggest what broke the MOSFET, and an improved design is proposed.

Nyckelord
Keyword
MOSFET, Inductive load, Inductive switching

Abstract

This report is the basis for a Bachelor of Science thesis in engineering done at Volvo Powertrain in Gothenburg.

The problem consisted of investigating a circuit with a PWM-controlled MOSFET driving a DC-motor. The problem was to investigate what caused the circuit to break the transistor. Finally an improvement of the circuit is designed making the MOSFET withstand the stressful conditions exposed to.

An overall description of the problems with switching an inductive load using a MOSFET as switch is done. Some methods to protect the MOSFET from failure are also discussed.
Finally a discussion is held to suggest what broke the MOSFET, and an improved design is proposed.

Acknowledgements

I would especially like to thank my supervisor at Volvo Powertrain, Peter Grundberg for his support and guidance throughout the work and to my examiner Jonny Lindgren for tips and ideas.

Finally I would thank everybody else involved, such as my opponent Magnus Holmström, all involved personell at department 24461 Volvo Powertrain and my relative Stefan Karnevi who helpt me with the grammar in the report.

Table of contents

1 Introduction

1.1 Background

1.1.1 The Company

The work on the thesis has been done at Volvo Powertrain in Gothenburg at department 24460, Engine Management Systems (EMS). This department develop and design electronic control system for Volvo's heavy duty diesel engines, i.e. engines with between 4 and 16 liters cylinder displacement.

The specific responsibility of this department is to develop the electronic control unit, which is the “brain” in the control system. This includes development of electronic hardware, software, and practical application and optimization for every engine's specific needs and requirements. My specific work was performed within department 24461 where the hardware to the EMS is being developed.

1.1.2 Problem description

The problem consists of investigating what a MOSFET, acting as a switch in a circuit with an inductive load, is exposed to. Further more the problem consists of finding out why it would break down and what case caused it. The second part of the problem is to improve the robustness of the design, to make the transistor, and the other components included, withstand the stressful condition exposed to.

The solution with a freewheeling diode is not acceptable while the response of the motor, when the set point is adjusted will be to slow.

1.2 Purpose of this thesis

The purpose of this thesis is to examine how the MOSFET could be protected. The reader of this report should also get an in-depth understanding of the problem with switching MOSFETs with inductive loads, and what may happen.

1.3 List of abbreviations

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation.
ASIC	Application Specific Integrated Circuit.
ESD	Electro Static Discharge.
EMS	Engine Management Systems
EMF	ElectroMotive Force
ECU	Electronic Control Unit

1.4 Constraints

The thesis will only consider the specified circuit. The investigation and redesign will only be based on this circuit.
The results from the circuit measurements, performed during design verification, may not give sufficient information to proof any specific cause of failure. The switching process is very fast and high frequent, putting high demands on the measurement-equipment to be able to pick up any harmful phenomenon.

Important simulation constraints are the high frequency switching process in combination with limitations in the models. It is therefore difficult to make the simulation act close to reality. The motor, for example, was difficult to model because of its non-linearity.

The power supply is specified for values between 10 to 30 Volts. Supply voltages of 12 and 24 Volts are usual in vehicles. Due to the generator output power, the above mentioned voltage range is specified. A voltage level of 28V has been used in this thesis.

2 Theoretical background

2.1 The examined circuit

A simplified drawing of the circuit that has been investigated is shown in figure 2.1.

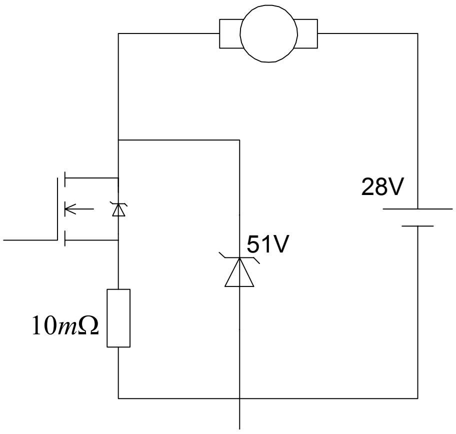


Figure 2.1

The motor is charged by a spring and is PWM-controlled to achieve the axis in right position, from 0 to 100 percent. See figure 2.2.

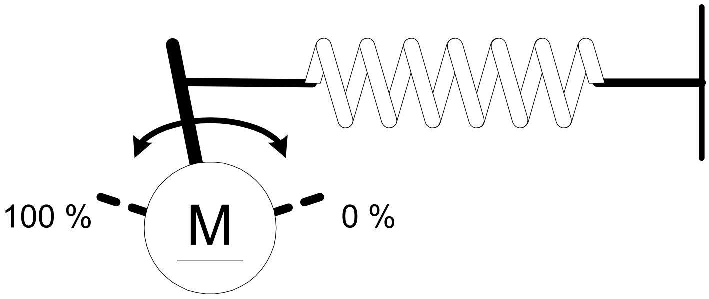


Figure 2.2

2.1.1 Function-description of the circuit

The circuit is controlled by an ASIC that generates the PWM-signal. The current through the resistor and the actual motor position are two inputs to the ASIC. The software in the ASIC propose a top current through the resistor, having the set point. The actual current and the position are then measured, and the system will adjust the motor position to the set point. The PWM-signal has a frequency of 200Hz, which corresponds to a period of 5ms.

Figure 2.3 Feedback system

When measuring on the gate in a testbench, the pulse on the gate of the MOSFET had a rise and falltime of about 60µs. Figure 2.4 shows the pulse on the gate with 55 % motor position. The duty cycle is about 32 %.

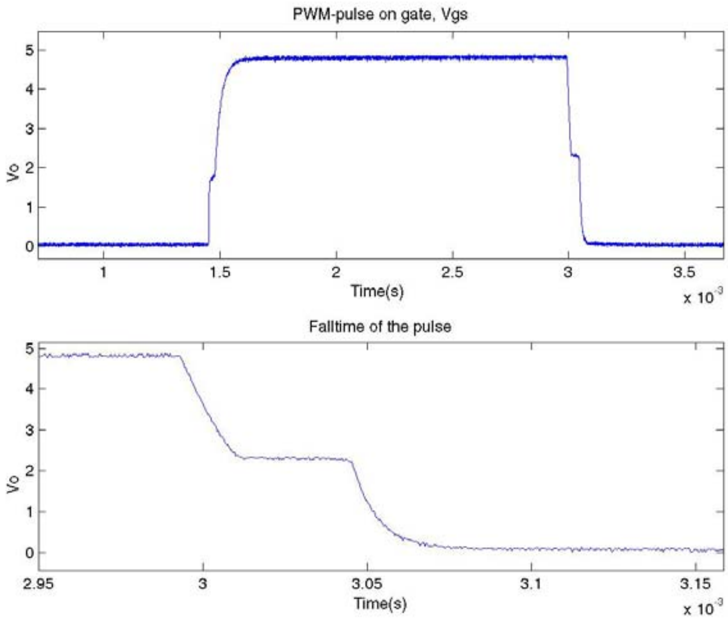


Figure 2.4

When the PWM-signal is high, the MOSFET is conducting and the motor is connected to ground. The motor starts and the current through it increases while the MOSFET is on.

When the desired current through the resistor is reached the PMW-signal goes low and turns the MOSFET off. The motor is however charged with energy and the inducing current want's to continue to flow. That's impossible, so the voltage is raised instead and when the voltage reaches the voltage of the external zenerdiode, the diode is forced to conduct. Now all current flows through the diode while the drainvoltage is higher than the zenerdiodes breakdown voltage.

2.2 *Model of the MOSFET*

2.2.1 Parasitic capacitors

The layout of the MOSFET on silicon leads to a number of stray capacitors between the layers. The most important capacitors to be considered during switching can be seen in figure 2.5.

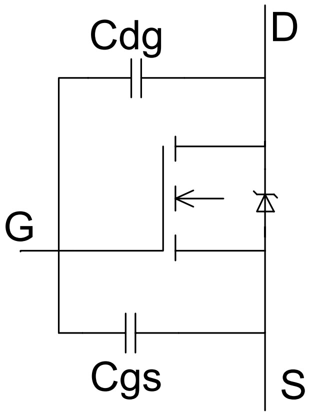


Figure 2.5

Cgs
This is the input capacitor that has to be charged and discharged during switching.

Cdg
This capacitor is a feedback path from the output to the input of the transistor. Care should be taken at high frequencies while it then will act as short circuit between the output and input of the MOSFET. It is also a nonlinear capacitor that decreases with increasing voltage over it.

2.2.2 Integral diode

Some MOSFETs have an intrinsic zenerdiode from drain-to-source. This is forced in conduction to protect the MOSFET from overvoltage. The value of the breakdown voltage is specified for the device.

2.3 Unclamped inductive switching

2.3.1 Problem with inductive load during switching

Unclamped inductive switching is the case when for example switching a MOSFET in a circuit with an inductive load. Unclamped switching means that there is no freewheeling diode to discharge the energy through when the device is turned off. Instead all the energy is dissipated in the device, which in this case is a MOSFET.

When the current through the inductance is quickly turned off the magnetic field cannot instantaneously collapse, a counter electromagnetic force is induced that can build up surprisingly high potentials over the switch. The faster the current is turned off the worse and higher this potential gets.

Mechanical switches often have spark-suppressions to protect the switch. Also when transistors are used protection is needed. The voltage transients that occur when switching off reach its maximum when switching the highest level of current from the load.

2.3.2 Calculations on expected transient

If the size of the inductor, the switching speed and the amount of current are known the equation below gives the expected potential.

$V = L * di/dt + V_{dd}$
L = the inductance (H)
di/dt = Switching speed
Vdd = Supply voltage

2.3.3 Reasons for MOSFET failure with inductive load

If a MOSFET is used as a switch there are two main reasons why it could break down. One is due to the stray capacitor from drain to gate of the MOSFET. The other has to do with the MOSFETs capability to withstand energy, i.e. the thermal resistivity.

2.3.3.1 Gate oxide

The layers of the gate and the source of the transistor are separated by a thin layer of oxide. This thin oxide is very sensitive to overvoltages and is therefore easy to puncture. This is the case with ESD when a high overvoltage is discharged through this layer. A rule of thumb is that if the maximum gate to source voltage of the MOSFET is exceeded by 2-3 times, the transistor is immediately destroyed.

When switching an inductive load the EMF in the inductor could produce high voltage transients when switched off. If the transient is high frequent it could easily be coupled to the gate of the transistor through the stray capacitor between drain and gate and destroy it.

2.3.3.2 Avalanche capability

A power MOSFET usually have an energy rating to tell how much energy they can withstand. Avalanching is the case when the intrinsic zenerdiode of the MOSFET is conducting, then avalanche current is flowing through the MOSFET. It's not flowing through the gate-enhanced channel as the drain current, however usually the maximum avalanche current is set equal to the maximum drain current. This is because the avalanche current will only decay from the value of the drain current when turned off.

The energy to be dissipated during avalanche can exceed what the device can withstand causing the device to fail. The factor that causes the failure is the temperature on the chip, i.e. when the MOSFET is subjected to repetitive energy the temperature rises and the MOSFET could break.

2.3.4 Protections

2.3.4.1 Diode clamping

To protect the transistor in harmful conditions there are some ways to use diodes and zenerdiodes in different combinations.

Active

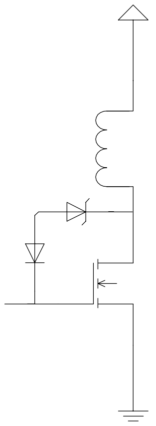


Figure 2.6

During turn off the zenerdiode clamps the drainvoltage at the specified voltage leading to a raise of the gatevoltage of the drainvoltage lowered by the zenervalue. This will turn the MOSFET on and let the induced current continue to flow through the MOSFET. The power dissipation in the MOSFET will be large since the drain voltage is clamped at the zenervalue when the current flows through the MOSFET.

Passive

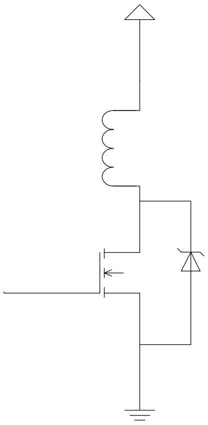


Figure 2.7

When the drain voltage reaches the voltage of the zenerdiode, it's forced to conduct. As long as the voltage stays at that level the current from the load continues to flow through the diode. The diode might have to be a power zenerdiode to deal with the power from the load. It's also of interest to use a fast diode, because elsewhere the MOSFET could get hurt during the time before the diode starts to act.

2.3.4.2 Snubber

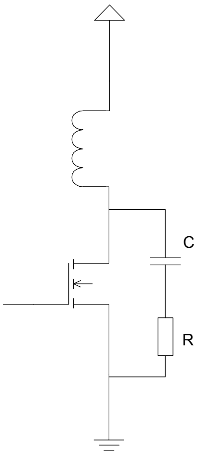


Figure 2.8

A RC-snubber can also be used to clamp the overvoltage. Note however that it absorbs energy during the whole switching period, not only at the end of it. Therefore it’s less efficient than a true voltage-clamping device.

2.3.5 Advantages and disadvantages with the protections

To compare the different protections, the purpose with the protection must be known. They work in different ways and must be chosen in consideration to the situation.

3 Investigation

3.1 Simulations

Instead of calculating how the induced voltage looks like, some simulations of the circuit were performed.
The PWM signal during the simulations was set to worst case, 32 % pulsewidth (55 % motor position), where the motor affects the circuit the most. This has been shown during practical tests and measurements done on the motor used.

3.1.1 Limitations with simulating

Simulations differ from the reality. For example the components don't "break" during simulation even if they should have done that in reality. The models used in the simulation can never behave exactly like a real component. Furthermore to make the simulations realistic all parasitic inductors, capacitors and also wire resistance have to be included.

3.1.2 Purpose

Simulation was made as a complement to measurements on the real circuit. During measurements no suspect observance was done that could prove the cause of failure.

3.1.3 Models

Models were searched for that would react as close to the used components and the reality as possible.

3.1.3.1 The transistor

At International Rectifier's website, the manufacture of the used n-channel MOSFET, a Spice model of the transistor was found.

3.1.3.2 DC-motor

This one was hard to model. The motors behavior changes during the different phases of the switching period. Due to this nonlinearity it was difficult to set up a good model. However, in the datasheet over the used motor some data were found. Just an inductance and a resistor in series arranged a decent model. Those values were found like the anchors resistance, 4.1Ohm and the inductance 6mH.

To refine the model the current through the motor in earlier design were measured and the model adjusted to have the same current during simulation. This was of course done with similar inputs to the MOSFET. The model turned out to match the motor best with values according to the figure

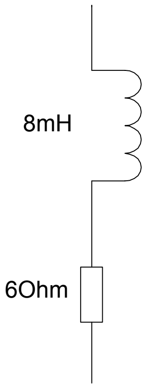


Figure 3.1

3.1.4 Simulating programs

3.1.4.1 Pspice

The first program used was a studentversion of Pspice from Cadence.
The circuit with a standard MOSFET (without intrinsic zenerdiode) and without external protection was simulated.

A transient analysis showed a large voltage transient of about 1.2kV to 2kV just as the MOSFET switches off.
With increasing falltime of the PWM-pulse the transient's voltage decreased and with a falltime of 1ms the voltagelevel of the transient was down to about 300V. This because the MOSFET turns off slower leading to less energy in the motor when there is no channel through the MOSFET anymore.

With the external zenerdiode this transient was totally clamped. Also with the model of the real MOSFET the transient was clamped. Several other simulations with different protections were also made, but due to the limitations with simulations, no harmful effects of interest were observed during the switching process. However, some strange oscillations occurred that will be clarified in the next chapter.

3.1.4.2 Multisim

In Multisim 2001 from Electronic workbench, the same simulations were performed as in Pspice, and with the same models. The results of these simulations were similar to those in Pspice. Some strange oscillations, similar to those in Psipce occurred after the zenerdiode stopped working.

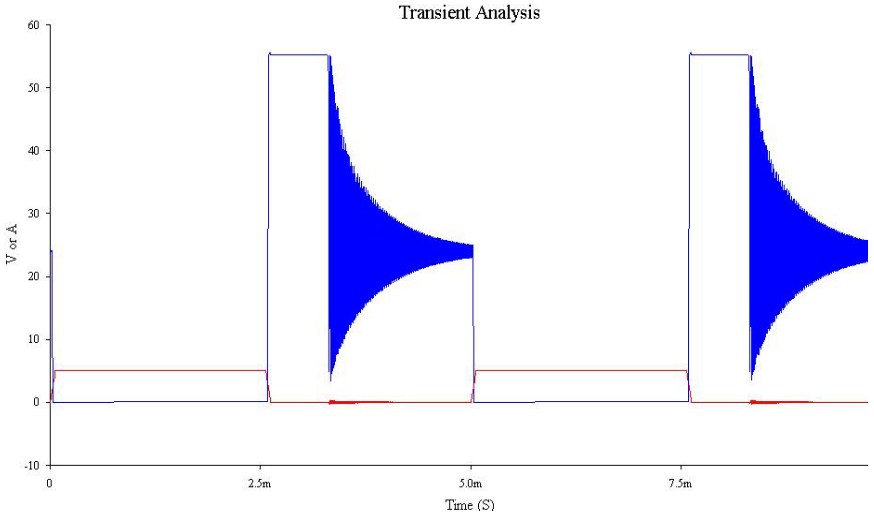


Figure 3.2

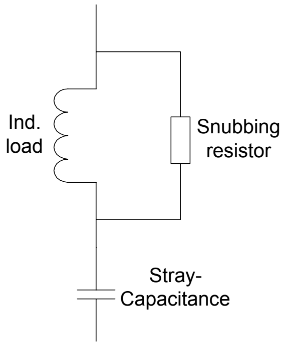


Figure 3.3 Snubber

These are due to oscillations between the inductive load and the stray capacitors in the circuit. This is more or less a consequence of the simulations differing from reality, where you for example have resistance in the wires. To damp these oscillations during the simulation a snubbing resistor in parallel with the load is efficient. To dimension the resistor the following relationship is used,
R = 2*pi*f. During the simulations a resistor of 5kΩ was used.

4 Discussion and results

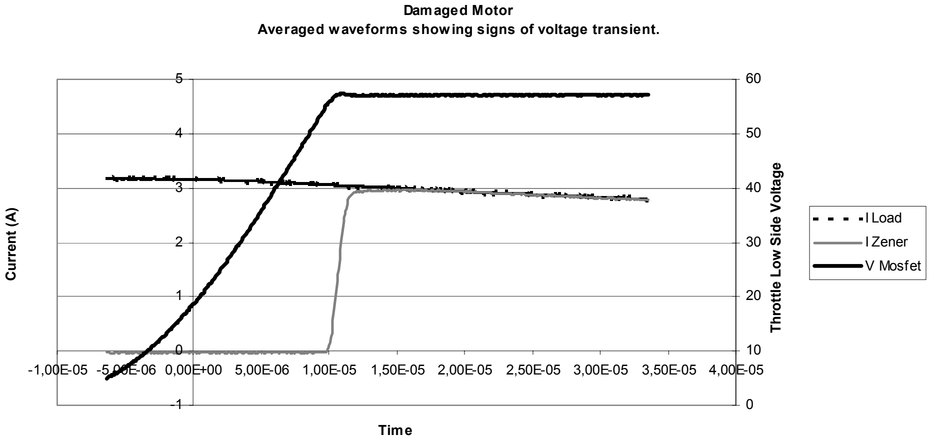
4.1 What caused the failure

4.1.1 Discussion

In this chapter a discussion will be held to indicate what caused the failure of the MOSFET in the investigated circuit. Conclusions will be drawn from the earlier chapters and no further explanations will be carried out here.

The first conclusion is the fact that when cutting the current through an inductance you will have to deal with the energy stored in it at that moment. This situation appears in every switching period when the PWM-signal goes low and the MOSFET turns off.

The only measurement that shows some indications of voltage transients from the load during turn off is this graph. It shows average waveforms of the measured voltages and currents during verification of the design. In the figure one can see a sign of a voltage transient at turn off, see “V_{MOSFET}” trace.



Figur 4.1

High frequency switching process could be one reason to no clear observance of a transient during measurements. The oscilloscopes sample frequency may not be high enough to deal with the transients. Two samples could then be placed on each side of the transient. On average waveforms, like the one in figure 4.1, this shows like a hunch.

During simulation with a standard MOSFET in Pspice a voltage transient of about 2kV appeared on the drain side of the MOSFET during switch off, see chapter 5.1.4.1. In reality it may not have been that large, but a transient of that size would easily break an unprotected transistor, if it were coupled to the gate.

The MOSFET is not completely unprotected, except during the short moment before the induced current is forced through the zenerdiode. That means that the external zenerdiode is dissipation nearly all the energy from the load, so that is not the factor causing the MOSFET to break down. The average power dissipation in the MOSFET was measured to 0.5W, which also contradicts that cause of failure.

The straycapacitor from drain to gate of the MOSFET is as described in chapter 4.2.1 a nonlinear capacitor that decreases with increasing voltage.
For the used MOSFET the size is about 150pF. With a high frequent transient on the drainside of the MOSFET this capacitor acts as short-circuit and the potential on the gate equals the potential of the gate for a short moment.

The thin oxidelayer (chapter 4.3.3.1) between the layers of the gate and source is very sensitive to overvoltage. The used n-channel MOSFET is rated for gate-source voltages of ±16V. A transient from drain coupled through the drain-gate capacitor would exceed this limit with a factor depending on voltage level of the transient.

4.1.2 Result

The result of the investigation point to the high frequency voltage spikes as causing factor to failure.
The discussion and the following list is what support this theory of failure.

- The resistance between gate and source turned out to be low impedance (~17Ω) when measured on the broken MOSFET. This indicates a punctured oxide layer.
- The graph in figure 6.1showing the indication of transients from the load during turn off.
- Simulating results from Pspice with the high voltage spike when the MOSFET turned off.

5 Remodeling of the circuit

The things to be kept in mind is that the PWM controlled N-channel MOSFET needs to be protected against the transients from the inductive motor, and the energy has to be dissipated somewhere when the MOSFET is no longer conducting.

This can be done in different ways. Either by make sure the problem doesn't appear at all, making it less pronounced and/or by taking care of the inducted energy.

Without external protection, all the energy from the load will be dissipated in the MOSFET. The average power dissipation is the causing factor to rising temperature and an eventual failure.
The power must be moved from the n-channel MOSFET also in the new design and it is of interest to lower the total power dissipation in the circuit as much as possible.

The n-channel MOSFET must in some way be protected against transients from the load. See chapter 4.3.4.1.1, where the principles of active voltage clamping are discussed.

5.1 Recirculation to the power supply

The redesign that will be considered here will let the inducted current circulate back to the power supply. The idea is to turn on a P-channel MOSFET when the N-channel MOSFET switches of, to let the current flow through the P-channel MOSFET back into the power supply.

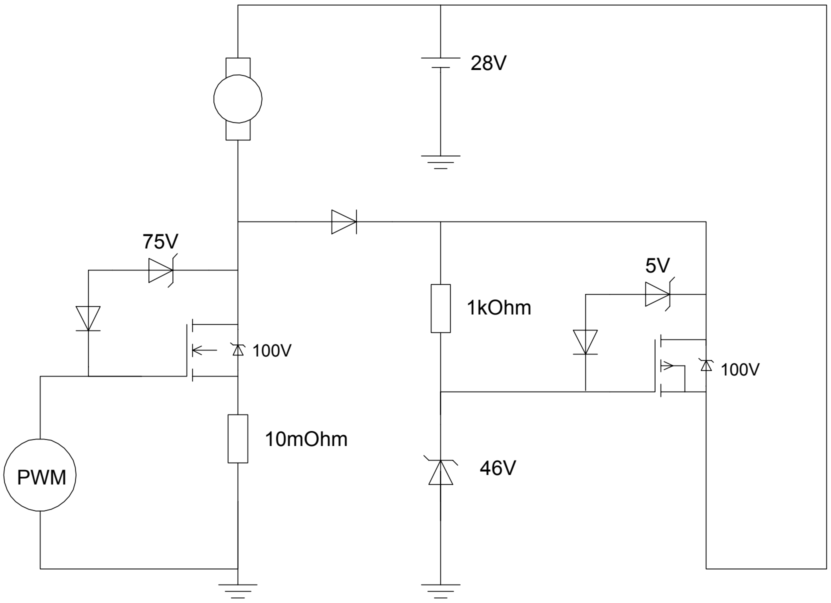


Figure 5.1 Wiring diagram of the new circuit.

5.1.1 Function of the new circuit

The phase in the switching process when the n-channel MSOFET is on, the circuit acts the same as before.

When the n-channel MOSFET turns off, the voltage will be clamped to 46 V over the inserted zenerdiode. The source voltage of the p-channel MOSFET will rise to 51 V and the source-gate voltage will be clamped to 5 V. The p-channel MOSFET turns on and the current flows through the MOSFET into the power supply. The characteristics of the motor will be maintained if the voltage is raised to 51V, as in the earlier design, before the P-channel MOSFET is switched on.

The inserted 1kΩ resistor forces the current to flow through the p-channel MOSFET.

5.1.2 Simulation and verification

Simulations were performed in Multisim, and the waveforms matched the expected. They were compared to those from the simulation of the investigated design.
The design was tested in a test bench at Volvo Powertrain, and some measurements were performed to make sure that the circuit worked out as planned. The control of the P-channel MOSFET, power dissipation over the two MOSFET's and the characteristic of the motor were monitored. Observing the waveform for the current through the motor checked the characteristic.

The equipment consisting the new design were running in testbench for about 2 hours with 55 % motor position (see chapter 3.1) with good results.

The design works with different power supply voltages without changing the functionality of the circuit. The control of the p-channel MOSFET is only dependent on voltages that are not affected by changes in the supply voltage.

5.1.3 P-channel MOSFET control

A p-channel MOSFET is turned in conduction when the gate-source voltage is pulled down to -5 V, i.e. the opposite in comparison to an n-channel MOSFET. This is achieved in the design by clamping the gate voltage to 46 V, the source-gate voltage is then clamped to 5V as the source voltage is increased above 51 V. The measurements on the circuit showed these characteristics on the gate and the source voltage.

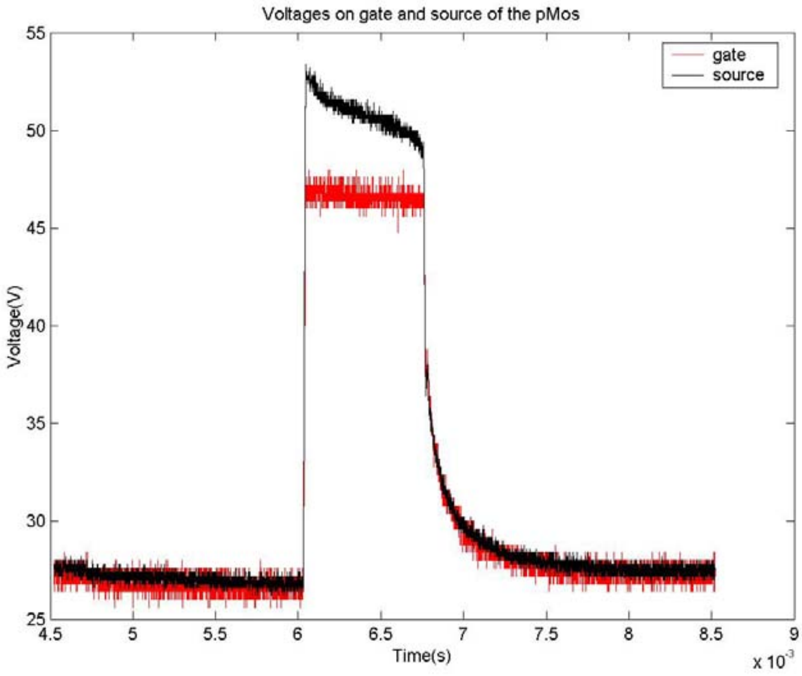


Figure 5.2

The voltage on the gate of the p-channel MOSFET will be drawn down to -5V only when the sourcevoltage is raised to 51V. The source-drain voltage is shown in figure 5.3.

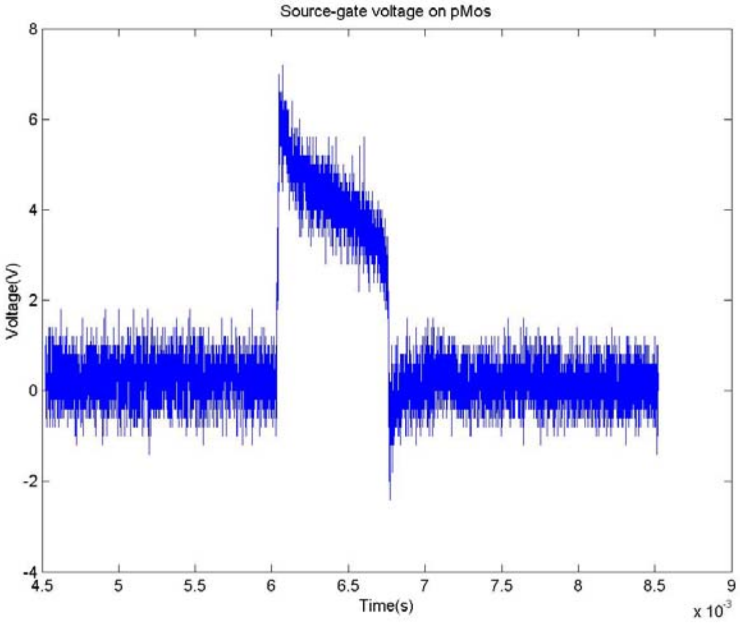


Figure 5.3

As long as the source voltage is 5 volt higher than the source voltage, a channel will be present through the MOSFET, and the current will flow through it. The 1kOhm’s resistor will force the current not to flow through the zenerdiode to ground.

5.1.4 Power dissipation

In earlier designs the power dissipation over the n-channel MOSFET has been as high as 10W in average without any external protection but active clamping of the gate. This caused the MOSFET to break due to high thermal resistance.
In the examined design the power dissipation over the n-channel MOSFET was 0.5W in average. The power was there moved to an external power zenerdiode instead.
With this improved design the power over the n-channel MOSFET is still 0.5W in average. The power over inserted p-channel MOSFET has been measured to be as low as around 3.8W in average, see figure 5.4. This because the voltage over the p-channel MOSFET is the voltage over the power zenerdiode, lowered by the voltage level of the power supply. In the performed measurements the power supply is set at 28V.

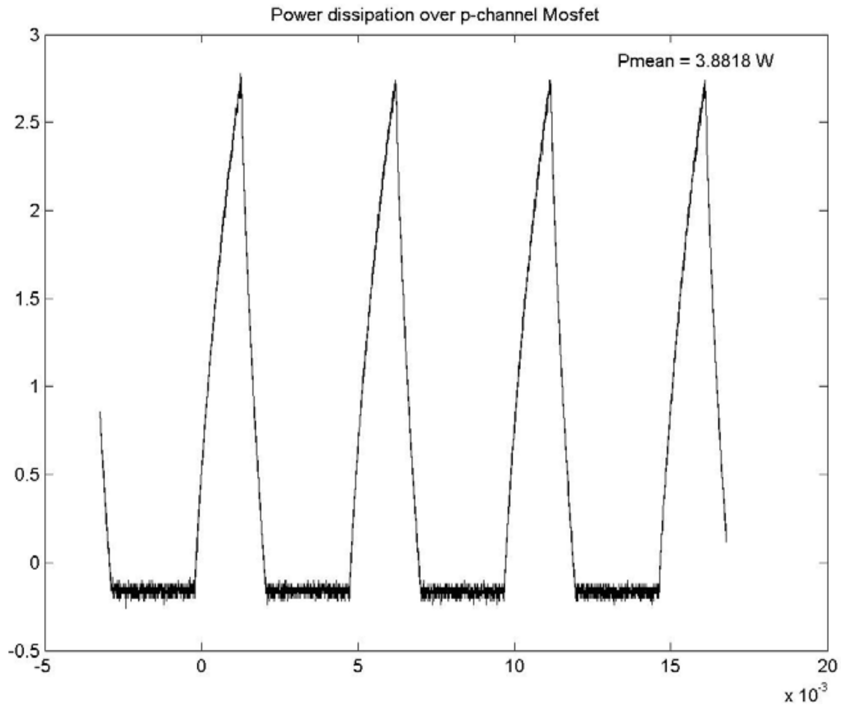


Figure 5.4

5.1.5 The characteristic of the motor

If the current through the motor during switching is the same as in the earlier design, the characteristics of the motor are unchanged. To check this, the waveform of the current in the new design was compared with the previous design. Figure 5.5.

The PWM signal was set to be the same in both tests.

A slight difference can be caused by variations in temperature and/or components and should be of no concern. The tests were performed immediately after each other with the same motor and no difference can be observed.

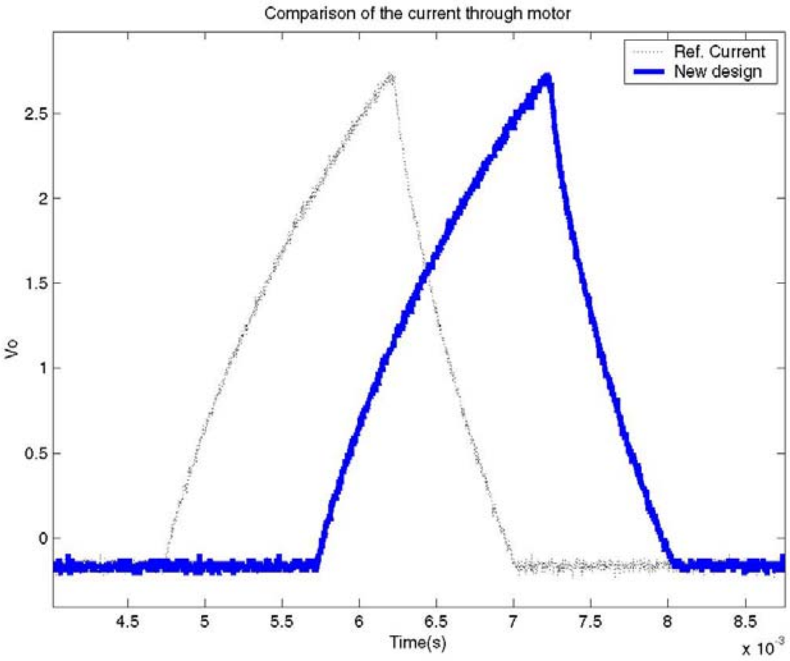


Figure 5.5

5.1.6 The final result

The circuit was wired together on a breadboard to facilitate the tests. The 46V zenerdiode consists of two zenerdiodes in serie with values of 30 and 16V respectively, because no zenerdiode of 46V was available at the moment.

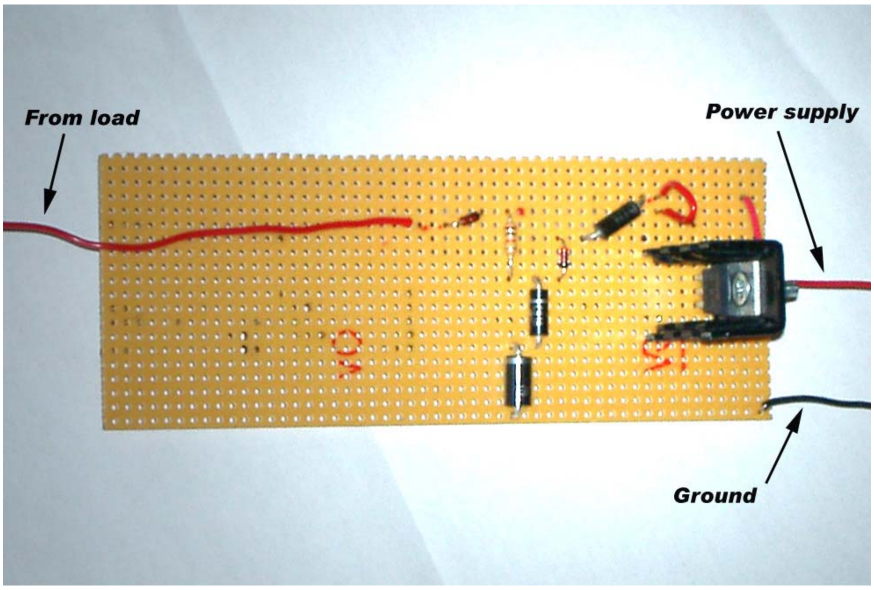


Figure 5.6

The total power dissipation in the new design has been reduced to about the half, which is a great advantage.

6 List of references

[1] Fischer ,K. and Schenai,K. (1996). Dynamics of power MOSFET switching.
IEEE transaction on electron devices, 43(6), 1007-15.

[2] Reimann,T., Krummer, R., Petzoldt, J. (1997) Active voltage clamping techniques for overvoltage protection of mos-controlled power transistors, Trondheim, Norway, September 8-10 1997.

[3] Vishay Siliconix (1994). AN601, Unclamped Inductive Switching Rugged MOSFETs For Rugged Environments. Feb 15, 1994

[4] Thorborg, K., "Power Electronics - in Theory and Practice". Studentlitteratur 1993, 1995, ISBN 91-44-38091-7.

[5] Application notes from International rectifier.
www.irf.com

LINKÖPING UNIVERSITY
ELECTRONIC PRESS

På svenska

Detta dokument hålls tillgängligt på Internet – eller dess framtida ersättare – under en längre tid från publiceringsdatum under förutsättning att inga extraordinära omständigheter uppstår.

Tillgång till dokumentet innebär tillstånd för var och en att läsa, ladda ner, skriva ut enstaka kopior för enskilt bruk och att använda det oförändrat för ickekommersiell forskning och för undervisning. Överföring av upphovsrätten vid en senare tidpunkt kan inte upphäva detta tillstånd. All annan användning av dokumentet kräver upphovsmannens medgivande. För att garantera äktheten, säkerheten och tillgängligheten finns det lösningar av teknisk och administrativ art.

Upphovsmannens ideella rätt innefattar rätt att bli nämnd som upphovsman i den omfattning som god sed kräver vid användning av dokumentet på ovan beskrivna sätt samt skydd mot att dokumentet ändras eller presenteras i sådan form eller i sådant sammanhang som är kränkande för upphovsmannens litterära eller konstnärliga anseende eller egenart.

För ytterligare information om Linköping University Electronic Press se förlagets hemsida http://www.ep.liu.se/

In English

The publishers will keep this document online on the Internet - or its possible replacement - for a considerable time from the date of publication barring exceptional circumstances.

The online availability of the document implies a permanent permission for anyone to read, to download, to print out single copies for your own use and to use it unchanged for any non-commercial research and educational purpose. Subsequent transfers of copyright cannot revoke this permission. All other uses of the document are conditional on the consent of the copyright owner. The publisher has taken technical and administrative measures to assure authenticity, security and accessibility.

According to intellectual property law the author has the right to be mentioned when his/her work is accessed as described above and to be protected against infringement.

For additional information about the Linköping University Electronic Press and its procedures for publication and for assurance of document integrity, please refer to its WWW home page: http://www.ep.liu.se/

© Tobias Ljunggren