SGS-THOMSON MICROELECTRONICS

APPLICATION NOTE

MOTOR CONTROL DESIGN USING VERTICAL SMART POWER ICs

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ABSTRACT

Readily available smart power devices can greatly simplify a power designer's design task by releasing him from the problems of designing high current control circuits.
Whilst making this aspect of the design transparent to the user, smart power ICs only require a standard logic compatible input signal.
These features are illustrated by practical examples of motor control using two different circuit configurations, a single switch and a full bridge circuit, working in continuous and in switched current modes.
The paper demonstrates that the problems of motor control (stalled motor, overload, etc..) are simply and successfully resolved by using smart power devices.
The devices contain an integrated vertical current flow power MOSFET, high side gate drive, maximum current control, protection circuits and a diagnostic status output.
The input and output control functions directly interface to a microprocessor allowing comprehensive control and fault diagnosis of the condition of the load, i.e. short circuit, open load and overload.
Designs safe-guarding the circuit against extreme working conditions are considered, such as a power supply disconnection with an inductive load.
Finally, future developments in smart power IC design for motor control are reviewed.

1.0 INTRODUCTION

In many application areas such as robotics, process control, automotive actuators, etc, the DC motor control board is, in effect, a power peripheral device of a micro-processor or micro-controller system.

Attaining high current, low power dissipation and effective diagnostic feedback with these peripheral boards can be a problem.

Using smart power ICs helps to overcome these difficulties and, additionally, provides a bonus: compact designs due to the reduced circuit size as a result of the integration.

The technology, one of three Vertical Intelligent Power (VIPower^{TM}) technologies, that includes, on a single silicon chip, a vertical current flow power MOSFET and analog and logic circuits, has allowed different families of devices to be produced that satisfy a wide range of applications.

Integrating a sense-FET on to the smart power ICs allows very high current, equal to that of discrete power MOSFET devices, to be controlled, resolving the problems of high current sensing even at high switching frequencies.

This leads to the possibility of making a wide range of interesting devices in a variety of packages with high power dissipation, some of which can be surface mounted.

The integration of analog and logic circuits that perform the various protection, diagnostic and current control functions, permit the design of a system where the peripheral circuit protects itself and the motor.

The micro-processor is able to handle the motor being aware of its working conditions.

2.0 MAXIMUM CURRENT LIMITATION AND CONTROL.

Current sense together with current limiting circuits are necessary in motor driving circuits, both for protection problems in overload conditions and in motor torque control.

The delay, the accuracy and the working mode of these circuits can be varied according to the application requirements and with the working mode (switching or continuous).

2.1 CURRENT SENSING.

The following disadvantages of the standard current sense circuits using a sense resistor or a current transformer highlight the advantages of using an integrated current sense circuit with a sense-FET:

- there is power dissipation ($P_d=R_{sens}I^2$)
- a high peak voltage is generated across the stray inductance due to the high switching speed (V_{peak} = L_{stray} di/dt).
- the noise tolerance of the control circuit is adversely affected due to capacitive coupling.

Figure 1 shows that the sense-FET works as a current mirror so only a part of the current flows through the sense resistor, hence the power dissipation in the sense resistor is very low. In addition to this the integrated device requires less wiring. As a result there is less stray inductance. This, in turn, means it is possible to design a current sense circuit for very high switching speeds. If linear and accurate current control is not necessary, other methods of current sensing, such as detecting the saturation voltage or monitoring the junction temperature of the power sensing element, can be successfully employed.

Figure 2 shows the generic block diagram of the SGS-THOMSON Microelectronics high side intelligent switch.
Figure 3 shows that when a smart power IC temperature sense circuitry protects the device to prevent its destruction in over-current conditions, the over-temperature circuit turns the integrated power switch off at a safe operating temperature (140°C). This type of protection depends on the ability of the device to dissipate heat.

2.2 CURRENT LIMITING WITH VIPower

The current limiting can be achieved using linear or chopper techniques. Both solutions allow the current control to be relative to an external command and/or to internal parameters (internal references, junction temperature, voltage drop across the power transistor during the on state, etc.) as shown in figure 4 and 5.

3.0 DRIVING HIGH SIDE N-CHANNEL POWER MOSFETs

A Power MOSFET used in high side configuration requires a voltage greater than the power rail, high enough to turn on the device in full saturation.
This supply can have different configurations depending on the working conditions.
There are different methods of generating this gate drive voltage.
The charge pump technique can be used which is suitable for the continuous working mode or there is the bootstrap circuit which is suitable for switching applications.
These techniques or a combination of them can be integrated into the control circuit of the VIPower ICs, but some integration problems must be considered.

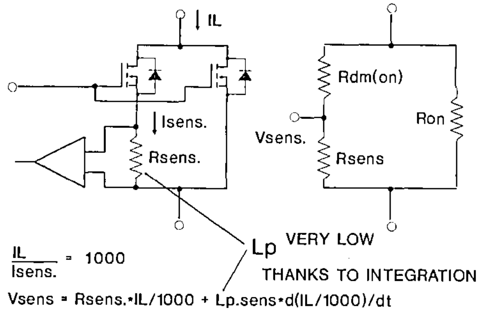

Figure 1 - Integrated current sense using a sense-FET and ON state equivalent circuit.

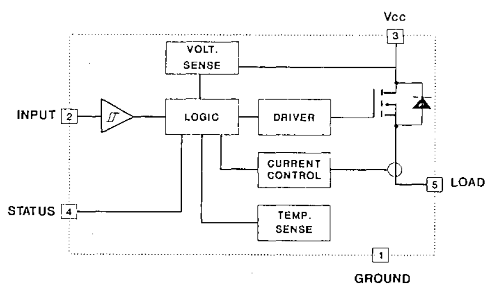

Figure 2 - Block diagram of a VIPower IC showing the main sense circuits.

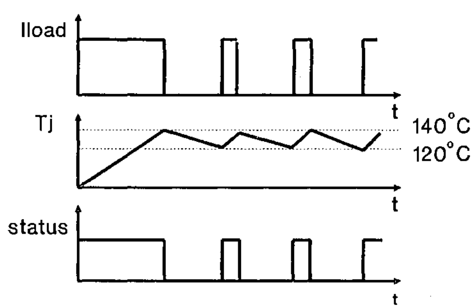

Figure 3 - Overload working mode of the VIPower intelligent switch, VN05

They are:
- the silicon area is proportional to capacitance value.
- number of pins must be limited to reduce the cost of the package.This means that the design of the drive circuit must be the best compromise between silicon area, number of pins and in the application under consideration that can have the following requirements:
- continuous working mode, switching working mode, or both.
- low switching losses (fast turn-on).
- low voltage applications typically 6 to 36V.
- complete turn-on of the power transistor in all working conditions.

Figure 6 shows the schematic of an integrated charge pump circuit that ensures sufficient gate-source voltage even if power supply is 5V or less.
This circuit multiplies the power supply voltage by three.
The integrated charge pump can only supply a few milliamperes and is therefore limited to use in continuous mode applications (i.e. solid state relays) because it needs a few hundred microseconds to generate enough charge to turn-on a Power MOSFET.
For switching applications, an external bootstrap capacitor can be connected to an internal control circuit, and, to ensure 100% duty cycle, both the charge pump and the bootstrap methods can be used (figure 7).
Figure 8 shows the turn-on switching behaviour of a VIPower IC with a Power MOSFET output using a bootstrap circuit to generate the gate drive voltage.
The switching time can be optimized in order to match low switching dissipation and electromagnetic compatibility.

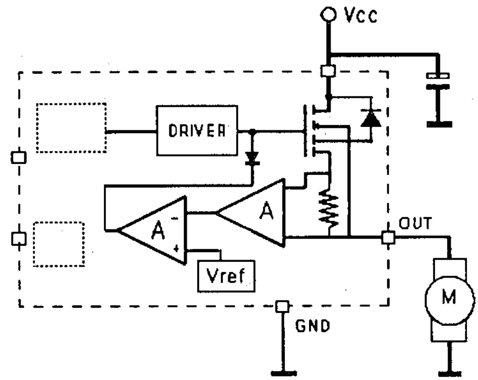

Figure 4 - Continuous current control in a VIPower IC

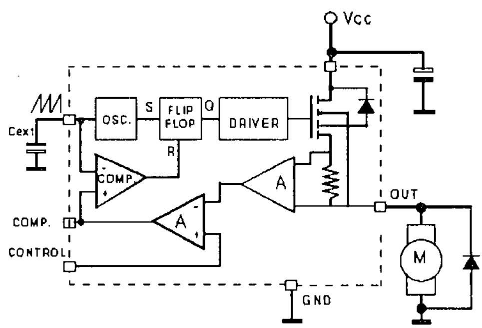

Figure 5 - Switched current control in a VIPower IC

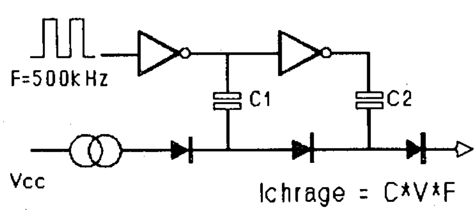

Figure 6 - Integrated charge pump that multiplies V_{cc} by 3.

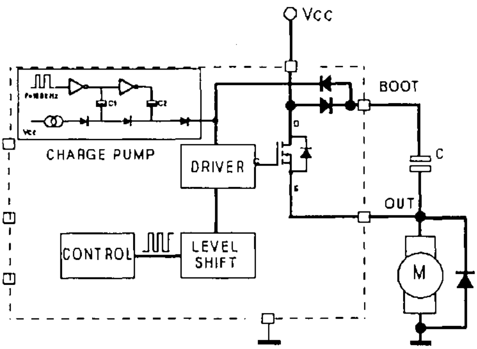

Figure 7 - Bootstrap and charge pump in a VIPower IC, allowing switching and continuous mode.

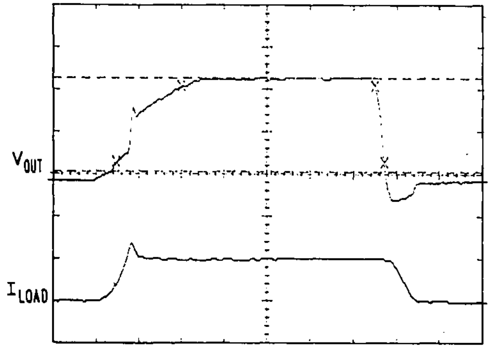

Figure 8 - Switching waveforms of output voltage and current in a VIPower IC V = 5V/div, I = 5A/div, t = 1 us/div

4.0 FAULT DIAGNOSTIC.

The ability to process the diagnostic information is very important in the design of fault tolerant systems.

In a motor drive circuit, this process can be complicated due to the changing working conditions of the motor and to the large variety of fault conditions, stalled motor, overload, open circuit due to the brush deterioration, etc.

The control circuit of a VIPower IC must be able to recognize these fault conditions and others, such as power supply failure, and differentiate between various fault conditions using a minimum of output pins and to be able to filter out false alarm signals.

This feature is achieved by the integration of a digital delay network and logic circuit that can, for example, operate as follows:

If a short circuit exists, when the device is turned on the VIPower IC internally limits the current and, after 33ms, it turns-off and the diagnostic output goes low.

If an open load exists (I_{out} < 50ma), when the device is turned on, then the diagnostic output goes low after 2ms.

If a fault condition appears during normal operation, the diagnostic output goes low immediately and the device turns-off.

If the device turns-off due to a fault condition, the control circuit must be reset by taking the input low.

These functions make it possible to discriminate between a false alarm signal given when the motor starts up and there is an in rush current or due to the inductive behaviour of the motor which can cause a low current for few µs.

By exploiting these features, it is possible to create a program able to interact with the VIPower IC and to identify the nature of the fault condition; this is illustrated in figure 9. A tri-state output can be used if only two fault conditions are to be identified.

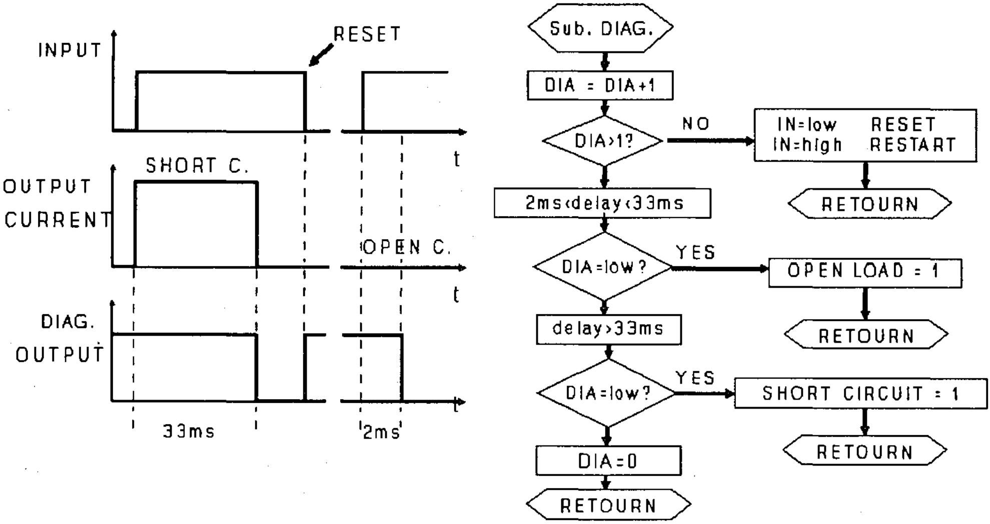

Figure 9 - Timing diagram of the diagnostic system in the VM201 intelligent switch and flow chart of a subroutine able to differentiate fault conditions.

5.0 MOTOR DRIVE USING TWO VERTICAL SMART POWER ICs IN A FULL BRIDGE CIRCUIT.

5.1 CIRCUIT DESCRIPTION.

The circuit in figure 10 shows how a very simple motor drive for an automotive electric window lift can be made using two high side smart power solid state relays and two discrete power MOSFETs in a full bridge configuration.

The SGS-THOMSON VIPower ICs used, VN05, have a very low $R_{DS(on)}$ (150 mΩ), maximum current limiting at 15A, under-voltage detection at 6.5V, thermal shut down (150°C), over-temperature and open circuit diagnostic output and a digital filter that makes the device able to distinguish between real and false fault conditions. The VM201, a power MOSFET plus the control circuitry integrated on to one silicon chip, provides all these features in a 5 pin HEPTAWATT package. Each half of the bridge is comprised of one VM201 and one standard power MOSFET.

The motor control board is CMOS and TTL compatible. This is possible because of the CMOS/TTL compatibility of the VIPower IC input and output and to the use of a low side CMOS buffer driver.

The free-wheel diodes are the intrinsic diodes of the discrete and integrated power MOSFETs. No power sense components are needed as the VIPower IC has an internal sense-FET.

In this application, the purpose of the diagnostic output (open collector), is to detect the stalled motor condition to protect the window at its extremes of travel and any accidental obstruction, eg an arm or dog!

This condition is characterised by an overload current caused by the stalled motor.
The ability of self decision of the VIPower IC and of interfacing software as shown in the previous section , 4, enables the circuit to filter a false stalled motor condition and to safeguard the power devices from over temperature stress.
Open load fault diagnosis can be used to recognize deterioration of the motor brushes.

5.2 BEHAVIOUR OF THE VIPower DEVICES.

The low $R_{DS(on)}$ (100mΩ), allows the devices to work at a high ambient temperature.
The worst case blockage of the window creates a current in the motor of up to 7A - 8A causing on-state power dissipation in the VIPower IC of 10W - 13W at a junction temperature, Tj = 100°C. This condition allows the devices to operate under the worst case conditions with a $R_{th\ junction\text{-}ambient}$ < 8°C/W, and with $T_{ambient}$ = 50°C. This avoids over-temperature detection during normal operation.
The figure 11 shows the behaviour of the current in the motor and of the diagnostic output during turn-on and turn-off. This behaviour is due to the overload current in the motor when the window reaches its limits of movement or is physically obstructed.

6.1 POWER SUPPLY DISCONNECTION DURING OPERATION.

In some applications, such as process controls, the main power supply protection system can, under certain conditions, disconnect the power supply during operation.
If the loads are motors or inductive loads, the collapsing magnetic field of the inductance can drive the output pin negative. The control circuit of the IC is isolated from the power MOSFET output section by an isolating junction which forms a well in the silicon surface; the control circuitry is constructed in this well. If the MOSFET cannot provide the current flow and the junction of the control circuit insulation is forward biased, this condition can prove critical due to the activation of parasitic components, and cause a current to flow though the control pins of the VIPower IC that can damage or disturb the micro-processor circuits.
The simple solution shown in figure 12, shows a clamping diode that enables the output power-MOSFET to conduct the energy stored in the inductance. Figure 13 shows the VIPower IC behaviour during a power supply disconnection; however the negative voltage spike on the diagnostic output can cause an incorrect feedback signal which can be avoided by using an R/C filter.

7.0 FUTURE DEVELOPMENT OF MOTOR DRIVE ICs.

The future trends of the VIPower technology, using a vertical current flow power MOSFET, are influenced by the needs in specific applications to drastically reduce the dimension of the high current motor control boards.
Surface mounting packages are being developed to satisfy this requirement. They will allow mounting in hybrid circuits without the need for sophisticated die attach technology.
These packages will have outlines that conform to those of existing packages, together with thermal resistance characteristics suitable for power devices.

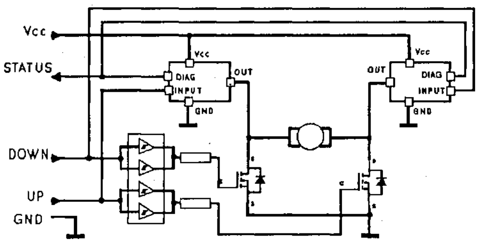

Figure 10 - Motor drive for a window lift with two VM201 intelligent switches

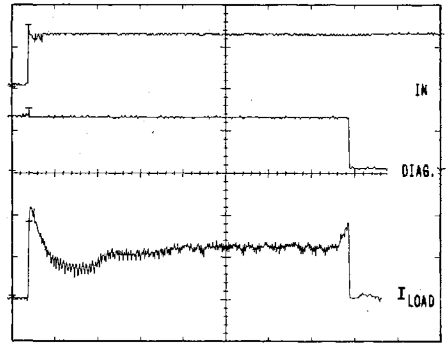

Figure 11 - The VM201 during the in rush current at turn-on of the left window and at turn-off due to a stalled condition. INPUT=5V/div, DIAG=5V/div, OUTPUT CURRENT=5A/div, t=100ms/div

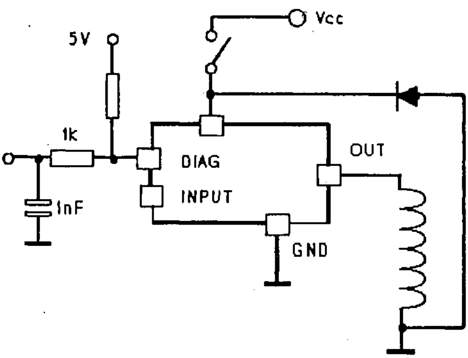

Figure 12 - Protection from accidental power supply disconnection

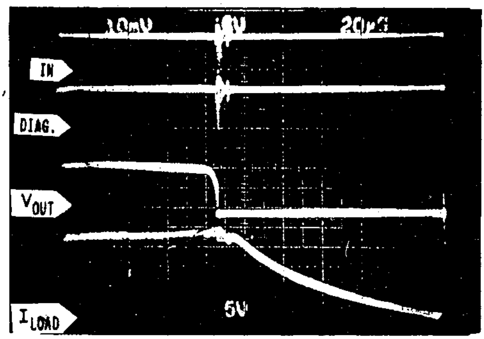

Figure 13 - Waveforms during power supply disconnection.
IN=5V/div, DIAG=5V/div, OUT=10V/div, Iout=2A/div

7.1 CONFIGURATIONS OF NEW LOW VOLTAGE MOTOR DRIVE ICs.

To give some concrete example of future ICs, typically power tool applications with a single switch are considered.

For full bridge applications, where bi-directional rotation is required, a double high side driver with two external low side discrete power MOSFETs can be employed, figure 14. A full bridge cannot be integrated in one chip using only VIPower technology because the substrate of the IC forms a common drain to all the integrated power MOSFETs.

However this can be resolved by using both

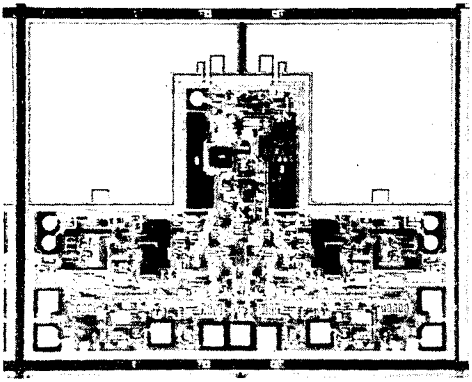

Figure 14 - Chip of a double side driver

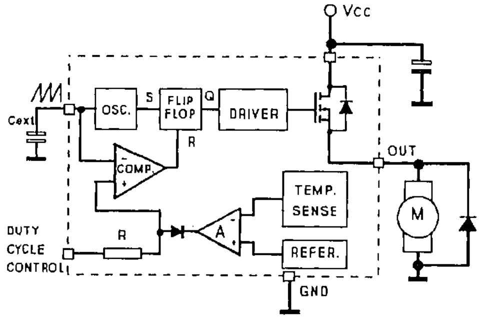

Figure 15 - Limitation of the maximum CHIP temperature using a temperature feedback.

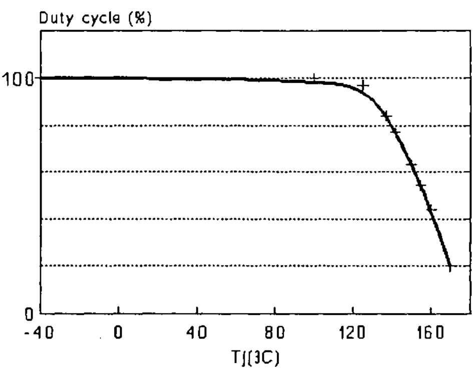

Figure 16 - Duty cycle reduction vs Tj in the circuit of Fig. 15.

the VIPower and the BCD (Bipolar CMOS DMOS) technologies. Figures 15 and 17 show examples of possible single switch mode motor control configurations integrated in VIPower technology:

Figure 15: The micro-processor sets the maximum duty cycle and the VIPower IC internally limits the operating junction temperature; when the temperature reaches the maximum value, the temperature sense circuit operates in a feed-back loop and reduces the duty cycle (figure 16) in order to maintain the junction temperature at a safe value; This feature allows the motor to work in overload conditions safeguarding the power ICs from the stress of over-temperature.

Figure 17: Speed and maximum torque control of the motor can be achieved using a feed-back control circuit for the current and the motor speed, the latter employing a frequency to voltage converter; this gives the possibility of precise control including motor acceleration control.

All these applications see the VIPower IC as a peripheral device of a micro-processor with the ability to make decisions; The VIPower IC, however, is self protected from over-current, over-temperature, etc, and is able to exercise rapid control over the process.

8.0 CONCLUSION.

Several problems are solved by the integration of a power MOSFET with appropriate control circuitry on one silicon chip. It achieves:

high current capability in a compact package

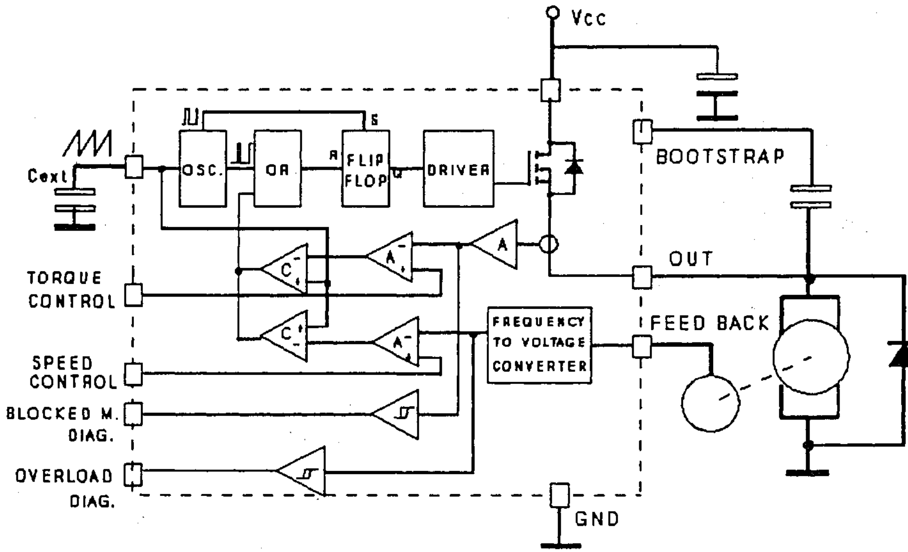

Figure 17 -Torque and/or speed motor control implementation

- no power dissipation in the sensing element using a sense-FET.
- no interference of the control circuit by stray induction in the external wiring.
- the ability to drive a power device from a logic circuit.
- diagnostic control and information.

The internal protection, the ruggedness and the wide range of working frequency make the VIPower IC able to drive motors and inductive loads under all working conditions without external protection.

The CMOS/TTL compatibility of the input and the output signals directly interface with a micro-processor and allow it to be used in many applications such as automotive actuators, process control, and robotics.

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