Digital Control for Brush DC Motor

Thierry Castagnet and Jean Nicolai

Abstract—**In home appliances applications the brush D.C. motor, driven by a chopper, can be controlled by a standard microcontroller. However people often consider the microcontrollers as not suitable for power environment because of their limited computing speed or noise immunity problems.**

This paper shows how a cost effective digital motor drive can be designed by combining a chopper and an 8 bits microcontroller: the speed is simply controlled through direct voltage compensation and motor power limitation.

The microcontroller implements both motor control and interface functions of the application: it replaces the analog circuits of the conventional motor control. Performances and practical results are given for a 300 W / 12000 RPM motor drive.

I. Introduction

In home appliance applications the permanent magnet dc motor is replacing today the ac universal motor in order to improve speed/drive performance.

Traditionally, the control of this motor is implemented by analog circuits and with an associated microcontroller, dedicated only to user interface function. This paper shows that a low-end microcontroller can control directly a chopper-driven dc motor in addition to these interface functions. In our example the adjustable speed drive is made with a 300-W–12 000-r/min permanent magnet dc motor for a food processor application.

II. The Permanent Magnet dc Motor and its Converter

The brush dc motor can be associated to a chopper control circuit. This adjustable speed drive controls the load in one rotation direction without any electrical braking; such operations are adapted to applications like food processors, drills, or washing machines.

The design of the control circuit is simplified with the use of insulated gate transistors in the chopper, and with the use of permanent magnets for the motor excitation. Permanent magnets (e.g., ferrite materials) replace the stator windings and suppress any excitation circuit; the motor has an independent excitation (see Fig. 1).

In home appliance applications the permanent magnet dc motor, driven by a chopper, is replacing the common ac universal motor when improved speed/drive performance is required (see [1] and Appendix A) for the following reasons.

- The motor efficiency is increased: the permanent magnets suppress excitation losses; and iron and copper motor losses are reduced because the motor current ripple is reduced (more than 50%) thanks to the dc mode operation and to a suitable motor voltage control.
- The motor noise is reduced: the 100-Hz torque ripple is reduced because of the motor current ripple reduction; and the switching frequency is quasi-inaudible. See [2].
- The motor voltage determines directly the speed because the excitation is independent; the speed is therefore stable, especially when the torque is varying quickly (during 1 s) and frequently (10 times).
- The operating speed range is increased because the motor can provide maximal torque (here $T_{max} = 2\text{N} \cdot \text{m}$) at low speed (less than 1000 r/min).

III. The Microcontroller: The Heart of the Motor Control

In home appliance or industrial applications, microcontrollers are usually dedicated to interfacing and sequence management. Here we will show that a microcontroller can also integrate the motor control. The microcontroller (MCU) is well adapted in order to implement in one package the whole functions of the application.

Our speed drive is controlled by an 8-bit microcontroller, the ST6260/65 (see Fig. 2). Such microcontrollers can meet interface and motor control requirements due to the following characteristics.

1) They make interface functions simple to design thanks to their 8-bit analog to digital converter (ADC), and to their many inputs/outputs (up to 21 I/O); these allow the MCU to measure sensors, manage actuators, and manage the user interface, for example, push buttons, potentiometers, keyboard, LED diodes, bargraph, or LCD displays.
2) They have adapted peripherals for the design of a motor speed drive: a pulse width modulation (PWM) timer for chopper control; an ADC with up to 13 inputs for voltage and current measurement; a nonmaskable interrupt (NMI) to generate safety protection in the central processor unit (CPU).
3) Their safety and immunity is fully compatible to line-connected circuits (hardware watchdog, careful supply layout, decoupled oscillator, filtered inputs) see [2].

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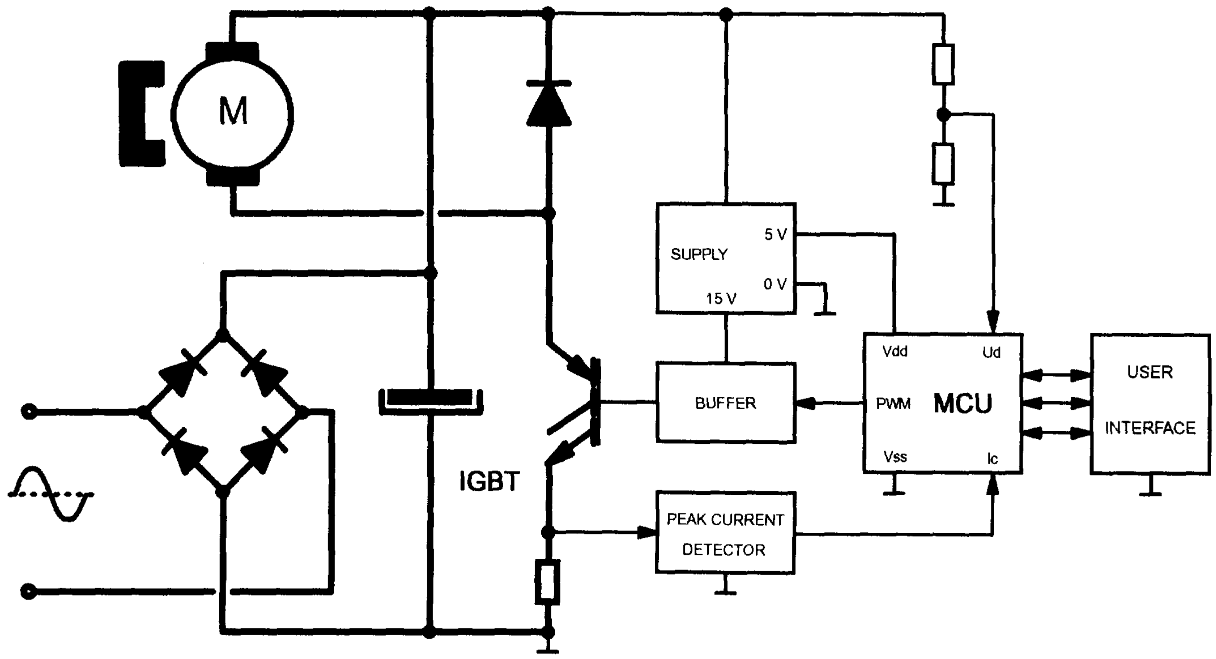


Fig. 1. Application block diagram. The microcontroller generates a PWM signal and controls the IGBT through the buffer-amplifier.

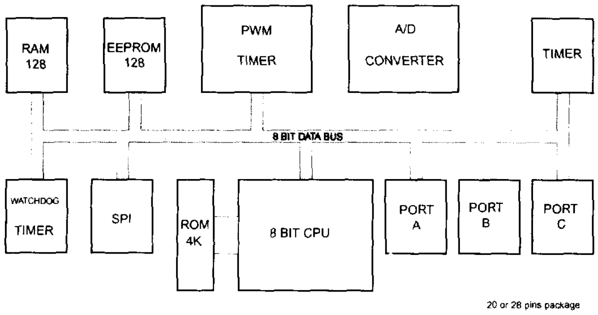


Fig. 2. Block diagram of the ST6260/65 microcontroller: PWM timer and A/D converter are adapted for motor control.

The performance criteria required for the speed control are the following.

—Accuracy on speed is not mandatory: the speed sensor is suppressed giving cost reduction; and the microcontroller adjusts directly the speed with the motor voltage.

—Direct voltage compensation makes the control of the motor voltage; so the speed is insensitive to the input power and to mains voltage variations; The motor current ripple is also reduced by this compensation.

—The user speed reference is defined by two +/− push buttons; its variation is adjusted by software and the start-up request speed is zero.

—The motor is protected against too big a load when the user request is out of the motor safe operating area. A 300-W motor power limitation is implemented, avoiding overheating and hard brush switching.

—The chosen chopper frequency is 8 kHz: the circuit can meet the RFI standards (VDE 875) with a small input filter while keeping a low switching noise level.

—Speed drive start-up is validated after a voltage check of the 230 V mains supply.

To achieve the speed drive, software functions have been implemented as shown in Fig. 3.

The *autoreload PWM timer* controls the chopper switching, generating the PWM signal. The CPU controls the duty cycle d and the switching period T_s by software (see Fig. 4). The duty cycle varies from 0 to 100%, with 0.4% (1/256) duty cycle resolution. The maximum switching frequency is 31 kHz; by software it has been adjusted to the requested 8 kHz.

The *direct voltage compensation* aims to keep the motor voltage V_{mot} and the speed constant, especially when the mains voltage is varying, or when the input power is transmitted to the motor. The duty cycle is modulated as a hyperbolic function of the direct voltage U_d around a reference point given by $d_0 =$ user request duty cycle and $U_{d\,\text{nom}}$ = nominal direct voltage:

$$V_{\text{mot}} = d \times U_d, \qquad V_{\text{mot}} = \text{const} = d_0 \times U_{d\,\text{nom}}.$$

(See Fig. 5.) To achieve this function U_d is measured and quantized in 32 steps and d_0 is quantized in 16 steps; duty cycle correction is picked up in a look-up table versus U_d and d_0. Then the correction is added to d_0 and the sum is loaded in the PWM timer.

The voltage compensation needs a table of 512 bytes, and takes 380 μs. The practical results are characterized in two ways.

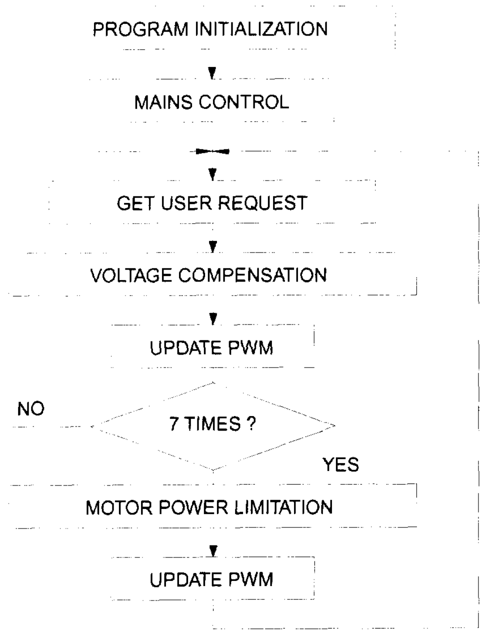


Fig. 3. Main algorithm for motor control; direct voltage compensation and motor power limitation are the key functions of the control.

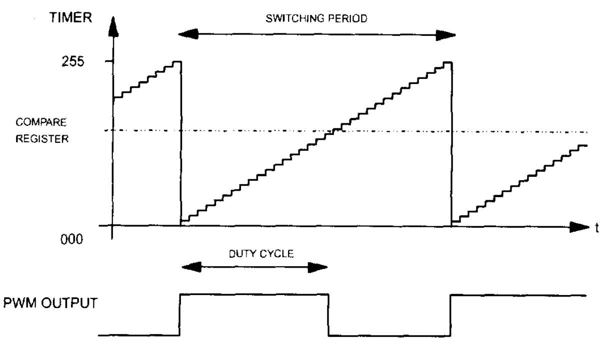


Fig. 4. Operation of the autoreload PWM timer. CPU controls the period T_s with the Reload register, and the duty cycle d with the Compare register; the timer counts independently of the CPU.

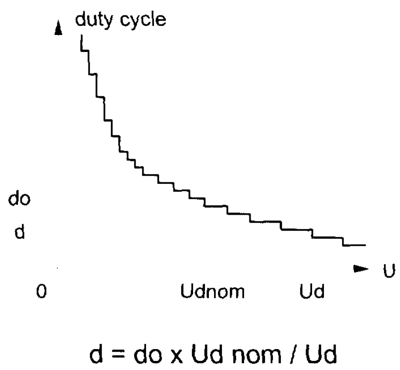


Fig. 5. Direct voltage compensation. The duty cycle d is modulated vs U_d and user request d_0.

—Fig. 6 shows how the motor voltage is independent of variations of U_d. This is the static performance; for one speed reference the V_{mot} variation is less than 10% on all the range of U_d; the speed becomes almost insensitive to the input power and mains voltage variations.

—Fig. 7 shows the dynamic influence of compensation on motor current ripple. It reduces this ripple by a factor of 2 in normal operation.

The *motor power limitation* is feasible when the peak motor current I_p is measured through a resistor or a SENSEFET. With a capacitor, diode, and the sample-and-hold method, this measurement is easy and accurate (see Fig. 10). The motor power limitation aims to limit d to a maximum duty cycle $d_{\max}$. Considering the motor current I_{mot} almost constant, $d_{\max}$ is defined as a hyperbolic function of U_d and I_{mot} (see Fig. 8):

$$P_{\text{mot}} = I_{\text{mot}} \times V_{\text{mot}} = I_{\text{mot}} \times U_d \times d,$$

$$P_{\text{mot}} \le P_{\max},$$

$$d < d_{\max} = P_{\max}/(U_d \times I_{\text{mot}}).$$

$d_{\max}$ is picked up from a look-up table versus U_d and I_{mot}, which are measured and quantized respectively in 16 and 32 steps. Power limitation needs a 512-byte table and is made every 3 ms. Fig. 9 shows the result with 300 W limitation. The two look-up tables are computed by a high-level language program or by hand; this method avoids calculation in the CPU, and allows a fast process. The tables used in this example are compatible for 230 V or 120 V mains applications. See [3].

The compensation and limitation tables can be modified and optimized to special requirements. The accuracy of results is mainly given by the ADC resolution (20 mV) and the basic step of converted measures ($1/2^n$ for $n \le 8$).

IV. The Switch: The Power Actuator of the Motor Control

The switch function is today made by insulated gate transistors like insulated gate bipolar transistors (IGBT) or power MOSFET transistors. Such transistors simplify and improve the chopper design because:

—their gate driver is simple; they are controlled by connecting a 15-V voltage source to the transistor gate.

—they are fast; the switching frequency can be inaudible (up to 16 kHz) because of their low turn-off energy.

The interface between the MCU and the switching transistor is made by a 15-V auxiliary supply that is connected to the 350 V dc supply, and by a buffer-amplifier that is driven directly by the PWM timer output. To this basic driver we can add other functions (see Fig. 11) such as:

—a transistor current sensor. A resistor or a SENSEFET can be used with an analog peak current detector (capacitance and diode); this measurement is necessary for power limitation.

—some fast transistor protection. The MCU cannot generally assume the protection because its reaction time is slower (12 μs typically) than the required response time

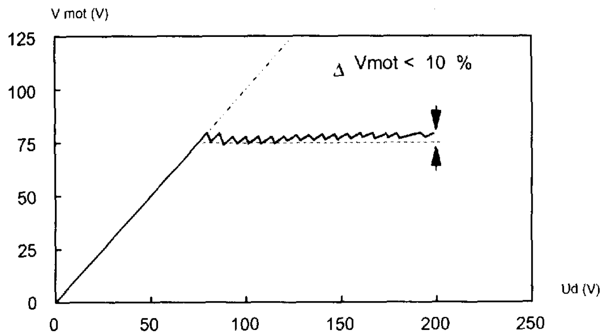


Fig. 6. Static performance of direct voltage compensation. The motor voltage tolerance is less than 10% for one speed reference.

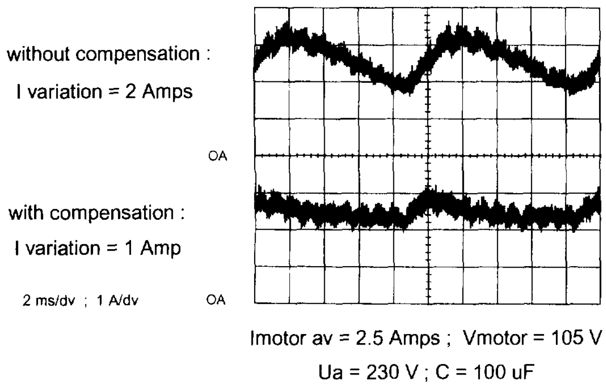


Fig. 7. Dynamic performance of the voltage compensation. It reduces the motor current ripple by 2; noise and losses are also reduced in the motor.

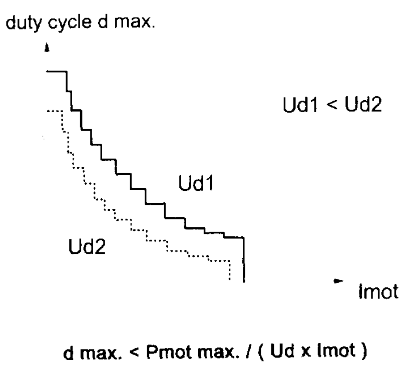


Fig. 8. Motor power limitation. This limitation is made by duty cycle limitation thanks to motor current and direct voltage measurement.

(less than 1 μs). With its own protection the transistor immunity is increased regarding the control. Short-circuit, overvoltage, and overtemperature protection are the key protections for good functional safety.

Here are two possible solutions which can be controlled directly by the ST6260 microcontroller:

—an IGBT version for home appliance applications with STGP10N50 (see Appendix B);

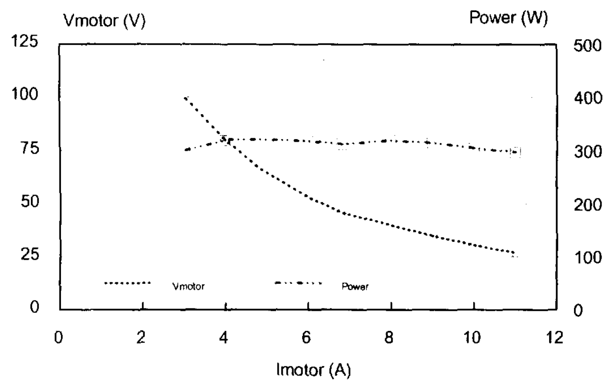


Fig. 9. Motor power limitation performance. Electrical motor power stays very close to 300 W; this limit is controlled by the computed data of the look-up table.

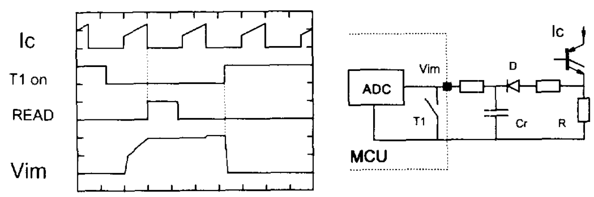


Fig. 10. Peak motor current sensing. (a) is independent from switching operations. It is made when T_1 is OFF; analog value is reset when T_1 turns on. (b) Basic diagram.

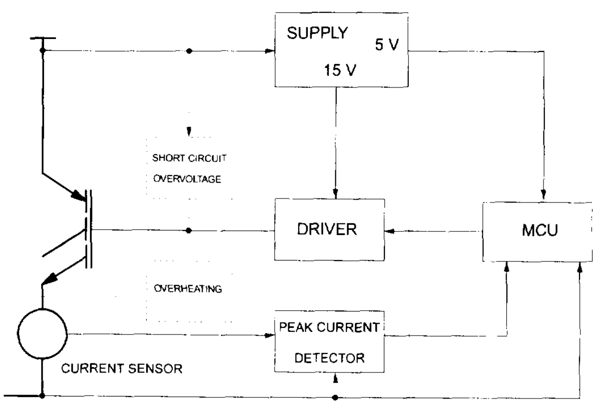


Fig. 11. Basic diagram of the MCU–switch interface. Fast transistor protection could be added to the driver functions.

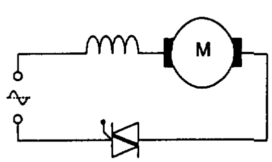
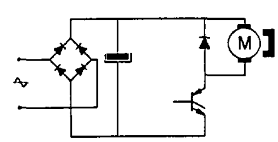
—an improved safe version with an intelligent power MOSFET, the VN440. This device integrates the driver, the SENSEFET, and fast protection against short-circuit, overtemperature, and overcurrent (see [4]).

V. Conclusion

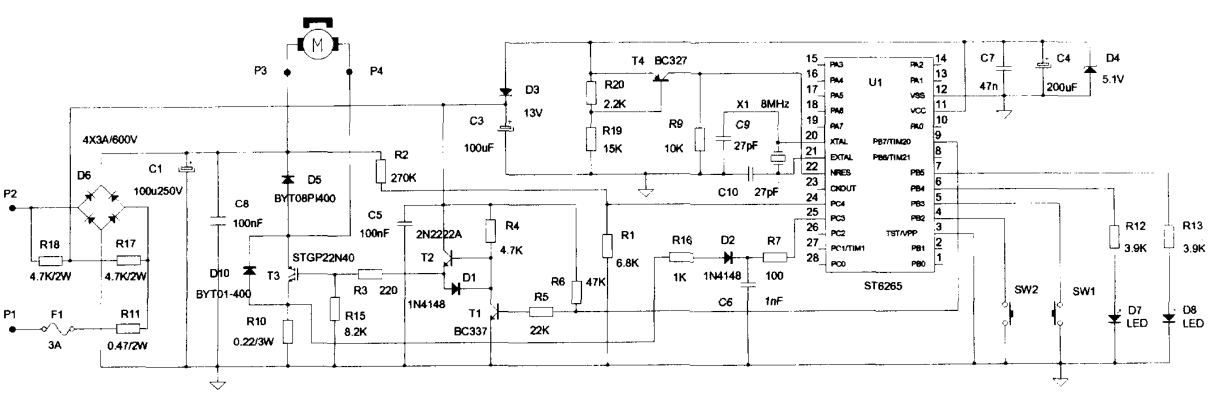
The design presented proposes a kit "microcontroller plus IGBT" that meets all requirements to control a permanent magnet dc motor in home appliances or industrial applications. This kit reduces the components count on the board because the microcontroller can integrate in one package all the functions of interface and motor control. The MCU plus IGBT becomes a flexible and adaptable solution for power control. The switching transistor (IGBT or VIPOWER) can be changed, and therefore the motor power (up to 4 kW); the motor control software program can be modified (speed regulation, current compensation), with integration of other functions (bus interfacing, heating, power supply control).

Appendix A

APPENDIX 1 : Comparison between the AC universal motor and the Permanent Magnet DC motor.

CRITERIA	AC UNIVERSAL MOTOR	PERMANENT MAGNET DC MOTOR
Driver Speed range (RPM) Speed control	- single triac 1000 ---> 25000 - runaway if no load - closed loop speed regulation is mandatory if large torque variation	- rectifier bridge + chopper - simple transistor driver ≈ 100 ---> 25000 - stable speed on all torque range - when accuracy is not required, speed sensor can be saved
Torque capability at low speed	- high but needs a control loop	- natural nominal torque
Motor efficiency Motor losses Driver losses	40 - 50% - 50 Hz copper and iron losses - lower (triac)	60 - 70% - no excitation losses - higher (rectifier + chopper)
Noise Magnetization	- higher 100 Hz torque ripple - brushes commutation - sensitive to iron saturation	- motor control reduces torque ripple - inaudible switching frequency - brushes commutation - overcurrent and overtemperature can demagnetize permanent magnets
BASIC DIAGRAM		

Appendix B



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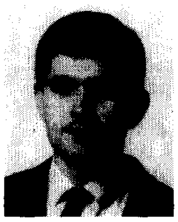

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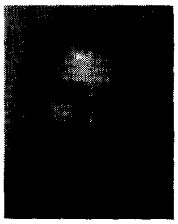

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