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IOR Rectifier

Eliminate Ripple Current Error from Motor Current Measurement

Eric Persson, Toshio Takahashi

Advanced Development Group
International Rectifier Corp.
U.S.A.

INTRODUCTION

Most motor drives today use measured current as a control variable. Simple AC drives only use current limit control, but motor phase current is used as the primary feedback variable in more advanced drives. Although the motor current of interest is relatively low bandwidth (a few hundred Hz), traditional pulse-width modulation (PWM) techniques add ripple current at the PWM frequency and its associated harmonics. For motors with large inductance values, like typical AC induction motors, the magnitude of the ripple current is small compared to the current of interest. For higher performance permanent magnet AC motors with low inductance, the magnitude of the ripple current can be quite large. To extract useful motor current information for feedback purposes, the system must either filter out the ripple current (which adds phase delay), or sample at the proper instant to effectively cancel-out the ripple. This requires separate sample and hold circuits in addition to the current measurement transducers. For short circuit protection, additional fast comparators are required for each motor phase as well. A new integrated circuit (IC) is presented, that simplifies this function by directly sampling motor phase current (synchronized to the PWM), and providing a digital output whose duty cycle is directly proportional to current, along with fast overcurrent shutdown logic.

TRADITIONAL MEASUREMENT METHODS

Current is typically measured with one of two methods: voltage drop across a resistor (resistive shunt), or magnetic transducer. Resistive shunt sensing has the advantage of a relatively low-cost sensor. The disadvantage is that there is a trade-off between sensitivity and power dissipated in the resistor. At higher currents, and therefore lower shunt resistance values, the inductive component of impedance begins to dominate. The transmission zero formed by the series RL combination therefore falls at a lower frequency. This can be compensated somewhat by cancelling with a suitably matched pole of an RC filter. Even with compensation, however, the useable upper frequency limit is reduced as the resistance value drops.

The second issue with resistive current sensing is *where* to measure the current. Since actual motor current is the desired value, the obvious choice is to put the sense resistor in series with the motor phase. The complication of that choice is that the signal of interest is a millivolt differential value across the sense resistor, but the common-mode voltage of the motor phase is typically hundreds of volts switching at high frequency with rapid dv/dt. There isn't a practical differential amplifier capable of rejecting that much common-mode voltage with the required bandwidth, so an alternative approach is required.

One common approach is to use an optically isolated amplifier in which the differential signal is modulated and communicated across the isolation barrier via infrared signal. The optical isolation effectively eliminates the common-mode voltage problem, but now the floating side of the isolator needs an isolated power supply. A further problem is that performance of typical optocouplers changes with temperature and degrades over time. An often overlooked issue is that the optocoupled amplifier output is a differential signal which requires a differential amplifier for scaling, and a level-shifting stage to work with the input of most analogue to digital (A/D) converters. This external amplifier can easily become the limiting factor for overall system performance. For example, to achieve 12-bit resolution, a high performance op-amp is a necessity. The cost of adding high performance op-amps to each current measurement channel rapidly increases the cost of this solution.

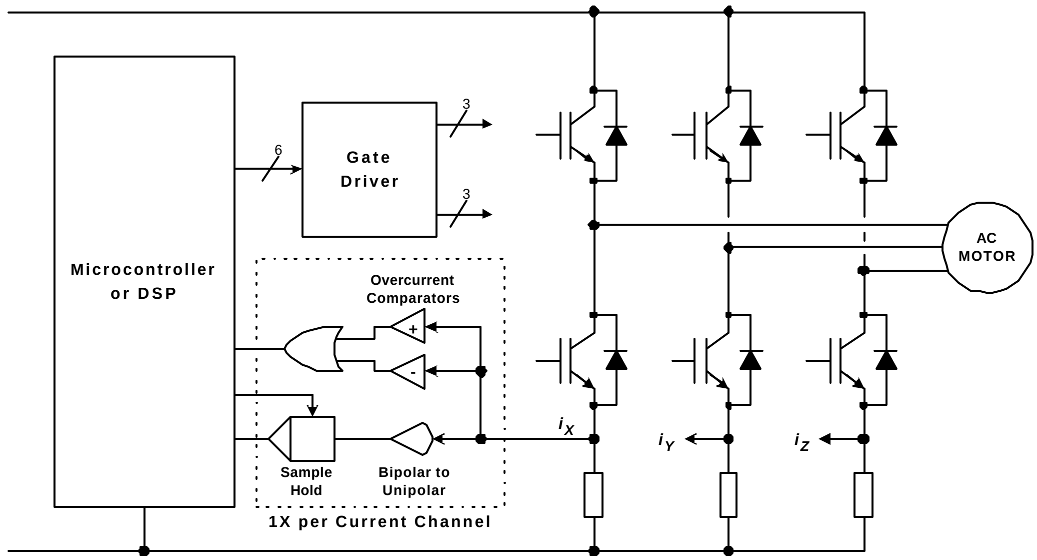

Figure 1: Traditional Current Sensing Method for Motor Drives

Another common alternative is to measure current through resistors on each low-side transistor emitter in the three-phase inverter as shown in Figure 1. As long as the measurement circuit is referenced to the DC bus common, this approach eliminates the common-mode voltage problem. However, a second problem arises: the measured current is no longer motor phase current, but half-bridge current. If the low side switch is conducting (through either the transistor or freewheeling diode) then the current is equal to that motor phase current. This certainly occurs periodically throughout the PWM cycle, but now a reconstruction circuit including a sample and hold amplifier is required. Moreover, in order to sample all three motor phase currents simultaneously (for zero phase-shift), *all three* low side switches must be conducting. This only happens at a zero vector state in which all three low side switches are on (corresponding to the negative peak of the PWM triangle wave in Figure 2). Even for conventional modulation methods like sinusoidal or space vector modulation, the width of the pulses to be measured can become very narrow, placing an increasing performance burden on the sample and hold circuit. When the modulation index meets and exceeds unity (as it does for overmodulation methods), however, the current pulses disappear altogether. Overmodulation methods require a different and more complex strategy for motor current reconstruction if this method of sensing is used.

Magnetic sensors, on the other hand, are isolated by their very nature. This means that motor phase current can be directly measured without the common mode voltage and reconstruction circuit problems just discussed. Traditional current transformers cannot be used because of the DC or very low frequency current components present in motor drives. Hall-effect current transducers solve that problem. They use a ring-type magnetic core with a Hall-effect semiconductor element placed in an air-gap to measure magnetic flux resulting from the current through the centre of the core. These so-called "open-loop" Hall-effect sensors suffer from several serious limitations, however. The magnetic flux in the core depends upon the magnetic properties of the core material, which is non-linear and temperature dependent. Moreover, the Hall element itself has temperature dependence, and does not exhibit wide bandwidth. Overall, the accuracy and bandwidth of open-loop Hall effect current sensors is not suitable for high performance AC drives.

A clever solution to the aforementioned limitations is found in the "closed-loop" Hall-effect current sensors. In these devices, a cancelling coil of e.g. 1,000 turns is wound upon the magnetic core described above. A built-in feedback amplifier drives current through the cancelling coil such that the flux (measured by the Hall-effect sensor) is always driven to zero – thus cancelling the ampere-turns generated by the current through the centre hole. The output of the current transducer is then that cancelling current, which is equal to the measured current scaled-down by the turns ratio. The majority of temperature dependent gain and core nonlinearities are also cancelled using this method, although some offset issues remain. The overall bandwidth and accuracy of these transducers has proven to be very good for motor drive applications. However, the complex construction and large magnetic cores required make these transducers larger and more costly than the alternatives. These transducers do not have any built-in overcurrent sensing, so additional reference threshold circuits and comparators (for + and -) must be added, further increasing the size, cost and complexity.

MEASUREMENT ERRORS DUE TO RIPPLE CURRENT

So far, the discussion of error sources has focused on the transducers themselves, or motor current reconstruction techniques. As mentioned in the introduction, PWM strategies introduce ripple current at a multiple of the PWM carrier frequency. To get at the desired motor phase current without the ripple (which is the objective for closing the current loop) it is possible to simply filter the ripple using an analogue low pass filter. However, unless the switching frequency is very high (>16 kHz), and the current loop bandwidth is very low (<200 Hz), this method is impractical because the low pass filter adds too much phase shift (delay) to the current loop. An alternative is to sample current at the peaks (positive, negative, or both) of the PWM carrier frequency in a centre-aligned PWM strategy, thereby sampling the average current at that moment [1]. Figure 2 shows an example of the PWM carrier frequency triangle wave, the three motor phase output voltages (U, V, W), motor phase current for the U-V phase and some additional timing waveforms to be explained later.

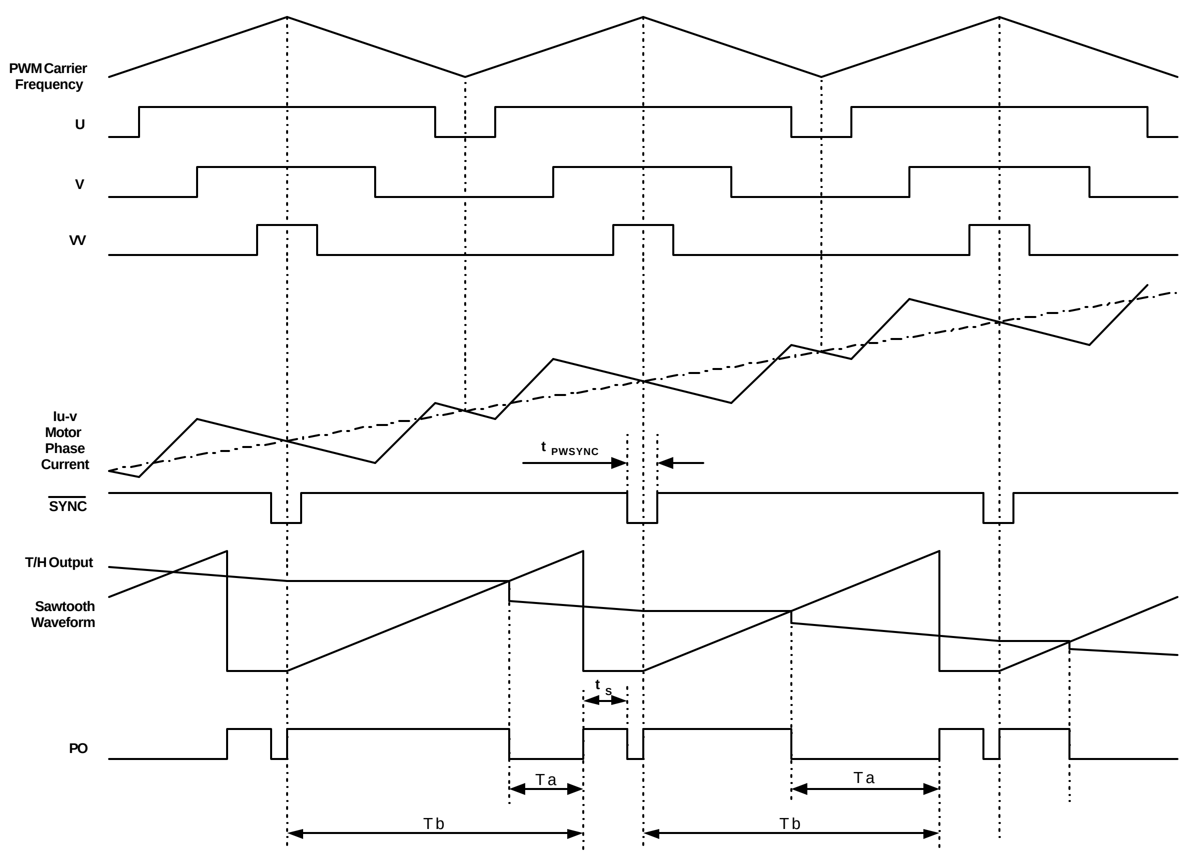

Figure 2: Timing Diagram

If the sample of motor current is to be accurate, it must align closely in time to the peaks of the PWM carrier, as timing errors move the sample point up or down the ramp of the ripple. Note that a consistently late sample will not result in a fixed offset, but a general distortion of the waveform, as the slope of the ramp varies with the overall motor phase current. The same is true of consistently early sample timing. A second concern is that the measurement transducer, optically or magnetically coupled in the previous examples, is now required to faithfully reproduce the motor current *with the full bandwidth of ripple* in order to obtain the best accuracy. Any phase delay due to transducer bandwidth limitations will result in inaccurate current sample acquisition as discussed above. If it were possible to move the sample and hold circuit to the motor side of the transducer, then the bandwidth limit would be a lesser problem.

SYNCHRONOUS SAMPLING IC

That is, in effect, exactly what the integrated circuit shown in the block diagram of Figure 3 does. Motor phase current is measured across an external sense resistor (200 mV peak) and applied to the input of the differential amplifier, between Vin+ and Vin-. The bipolar signal passes through a gain stage (x4.25) and is level-shifted to be a unipolar (positive only) signal. This full-bandwidth representation of motor current then passes through a track and hold amplifier that is synchronized to a low-side referenced **sync** signal. The measured sample is converted to a pulse width synchronized to the motor PWM frequency. The period of the PWM generator on the measurement IC is set by an external capacitor, and is selected to be slightly shorter than the motor PWM period. This allows for synchronization with a small set-up time. Motor current is then proportional to the duty cycle of the output waveform **Po** as seen in Figure 2. Temperature dependencies affect both the "on" time and the period of the Po waveform, so the duty cycle has an extremely low temperature dependence (40 ppm/°C).

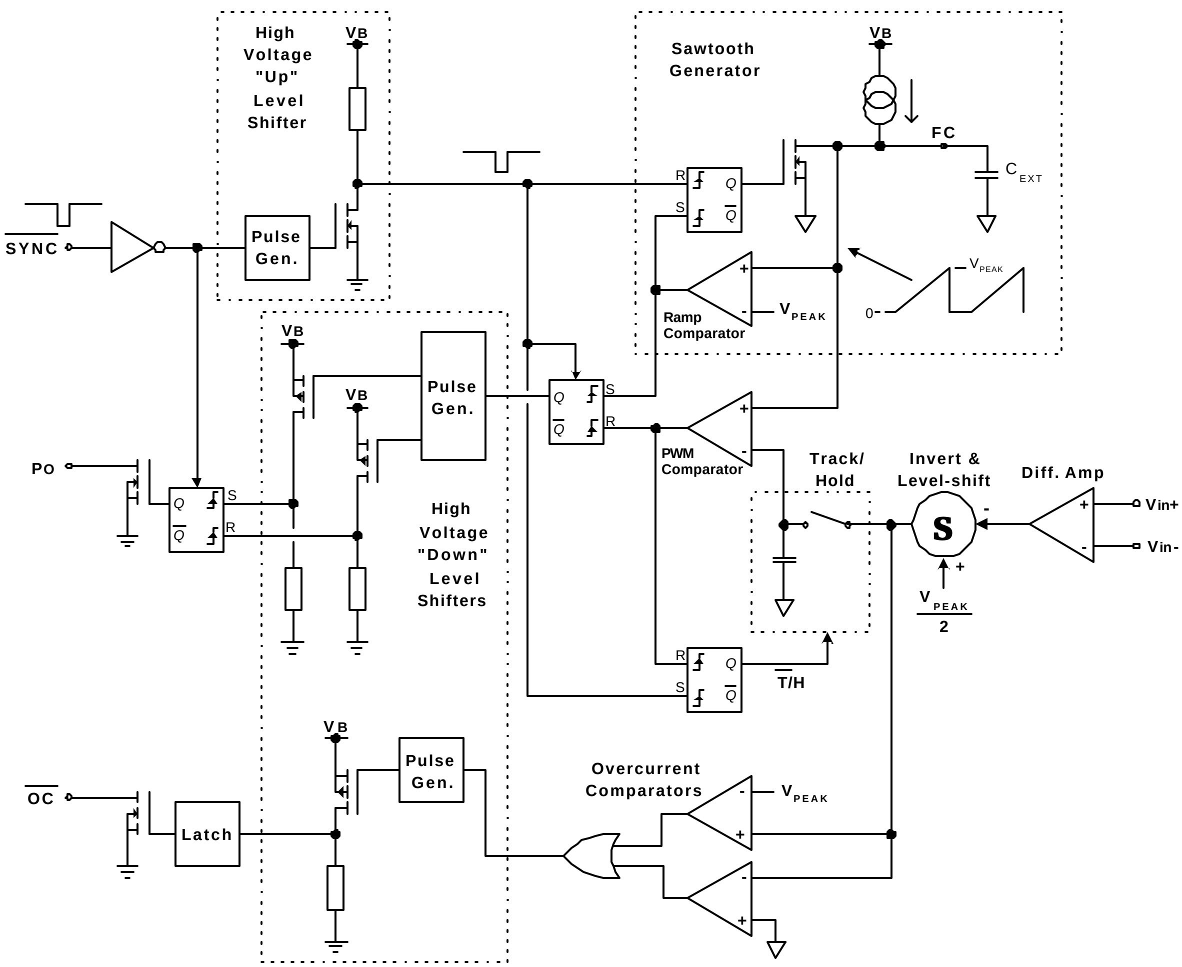

Figure 3: Block Diagram of Integrated Circuit

The IC also has an integrated fast overcurrent detection circuit (for both polarities of measured current). It can detect the overcurrent condition and send the signal to the low-side **OC** output in less than 1.5 us. This is twice as fast as optocoupler methods with built-in overcurrent detection

This IC is not truly isolated as the optical and magnetic transducers are, it merely level shifts the signals between the "high-side" (motor phase) and the "low-side" (negative DC bus – usually the common for drive circuits). The IC is fabricated using a junction isolation process with added features for negative voltage transient immunity. The level shifters communicate accurate digital timing signals in the presence of common-mode voltage as high as 1,200V and dv/dt rates of 50 V/ns. The high side circuits and amplifier require very low power (typically only 1mA) – low enough so that it can be powered by a simple bootstrap power supply.

The overall accuracy of the new IC is equivalent to 12-bit performance without the use of any expensive external op-amps. All that is required is a timer input on the DSP or microcontroller with a resolution of 10 ns or better (for 20 kHz PWM). The equivalent –3dB bandwidth of the IC is 15 kHz for a 20 kHz PWM carrier.

CONCLUSIONS

A new current measurement IC integrates the functions of sample and hold, level shifting, and fast overcurrent detection into one monolithic piece of Silicon featuring high accuracy and low temperature dependence. Sampling is synchronized to the motor PWM carrier frequency, and average motor current is measured directly, without the influence of PWM ripple current. Output from the IC is another PWM signal that can interface to a timer input on a DSP or microcontroller to achieve an overall level of performance consistent with 12-bit systems.

REFERENCES

[1] Richardson, J., "Implementation of a PWM Regular Sampling Strategy for AC Drives," *IEEE Power Electronics Specialist Conference Record,* 1989, pp. 649 - 656