Enhance AC induction motors with slip control, soft start

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Since AC induction motors have been established as the preferred choice for industrial motors and the need for reduced power in all aspects of design is ever present, the efficiency of these motors is critical. An optimised slip control mechanism is the key factor for achieving the required torque and efficiency performance in an AC induction motor. To achieve slip optimisation, a tightened control loop with highly integrated control logic becomes essential.

Most of the current solutions are based on processors that run fairly complex software programs to target efficient operation. Processor bandwidth and computation time in a software-based system significantly limit the responsiveness and, therefore, the power efficiency of these solutions. A more powerful processor implementation can give improved processing time and better power efficiency, but incurs additional cost.

Implementing control algorithms directly into FPGA logic gates can be a cost-effective alternative, with faster response times to I/O. Intellectual property (IP) can be acquired for design, and reprogrammable FPGAs allow for system upgrades as techniques improve. However, external processors and flash memory lookup tables (LUT) are still performance bottlenecks.

Highly integrated mixed-signal FPGAs with embedded nonvolatile memory and a soft or hard processor core provide the ideal solution for tightening the control loop and accelerating slip control processing, thereby improving AC motor efficiency. Since all processing power, LUTs and direct control algorithms can be integrated into a single reprogrammable chip, the solution is more accurate, efficient and cheaper than traditional solutions.

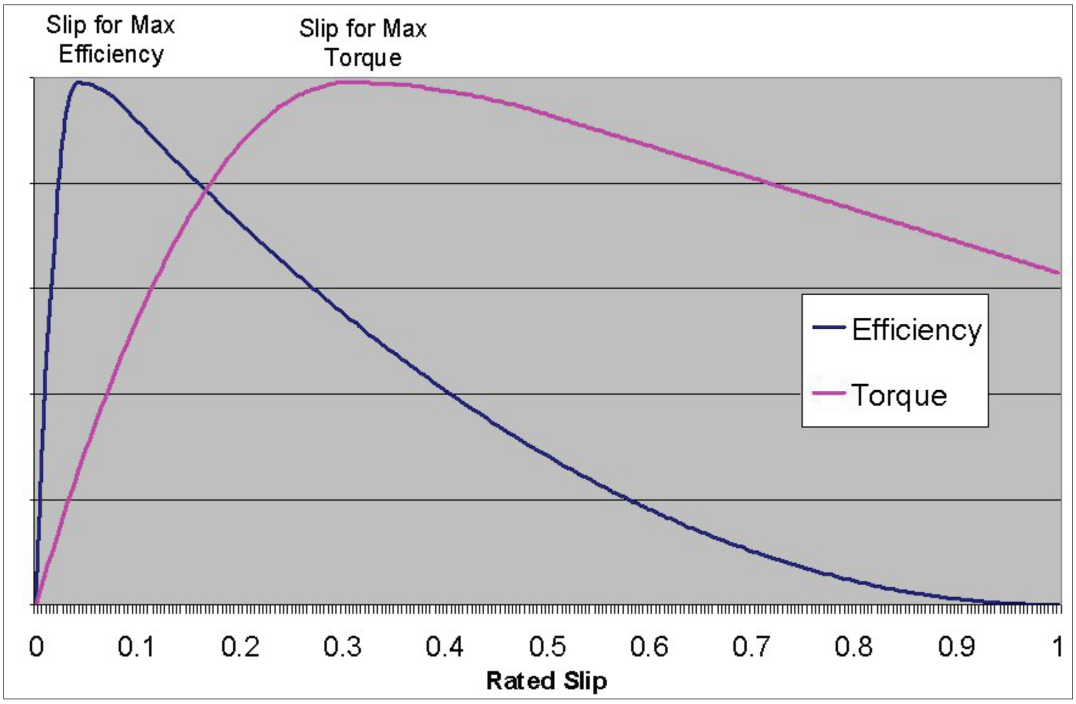

Figure 1: Torque and efficiency vs. slip.

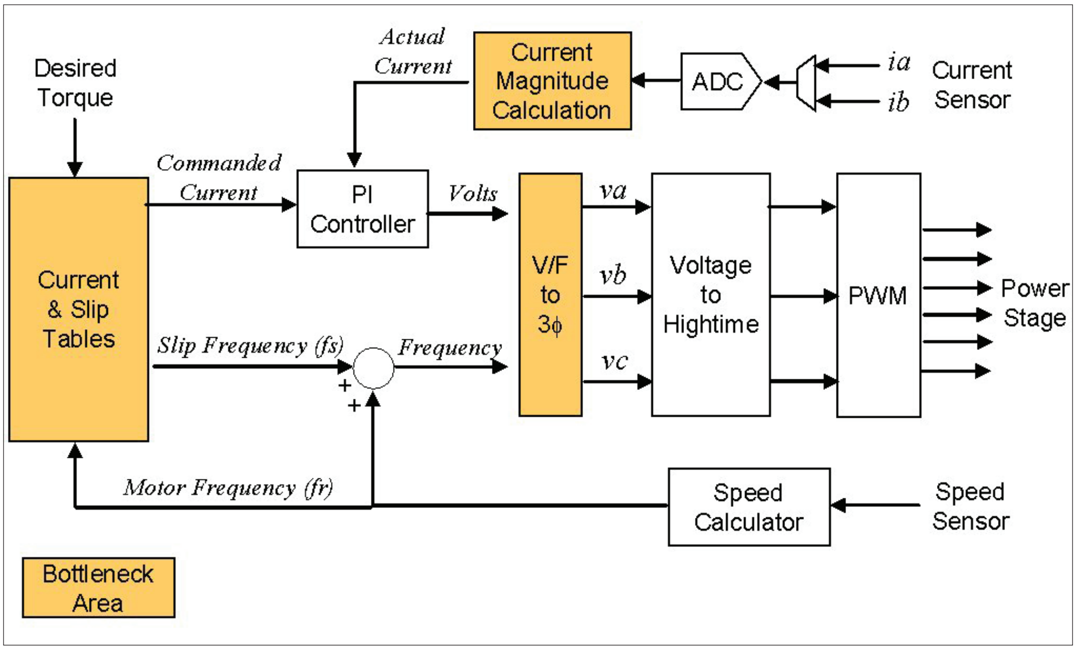

Figure 2: Slip control algorithm.

AC induction motor basics

In AC induction motors, three-phase electrical power supplied to the cage or static part of the device (stator) is converted into mechanical power in the rotating part of the device (rotor) through electromagnetic induction. There is no direct supply to the rotor. Current in the rotor is induced by the rotating magnetic field in the stator. Current in the rotor creates a magnetic field, which interacts with the rotating magnetic field in the stator causing the rotor to turn. The slip is defined as the ratio between the speed of the rotor and the speed of the rotating magnetic field in the stator.

Maximum efficiency in the induction motor is achieved when the rotor is turning almost as fast as the magnetic field in the stator—a slip close to zero. But in order to deliver increased torque for higher loads, a higher slip may be preferred as depicted in the diagram below. Optimised slip control uses algorithms to find the ideal balance at any point in time for either max efficiency or max torque. See **Figure 1** for efficiency/slip and torque/slip curves.

Slip calculation

The three-phase AC motor is designed to be operated from an AC supply, which has a fixed voltage and frequency. The supply frequency and the number of poles in the motor set the synchronous speed (speed of rotating field) of an AC motor.

If the supply frequency to the induction motor is

$f = p * n/2$

Where f is the supply frequency, p is the number of pole pairs, and n is the speed of the rotating field. Then the speed of the rotating field in an induction motor is

$n = 2f/p$ revs/second or $n = 120f/p$ revs/minute

And the rotor speed

$r = n(1-S)$

Where S is the slip. Slip is a ratio and therefore has no units.

Slip $S = n-r/n$

Slip frequency is the supply frequency required to maintain a desired Slip value.

For example, the synchronous speed of a four-pole motor, running from a 60-Hz AC line, is 120 * 60/4 = 1800 rpm. However, none of the motors run with a fixed level of loading. The load sets a slip in the motor and determines the actual speed of the motor shaft. The slip is significant in that it affects the torque and operation of the motor. In the control algorithm, slip control is the key factor in efficiency and performance of the motor.

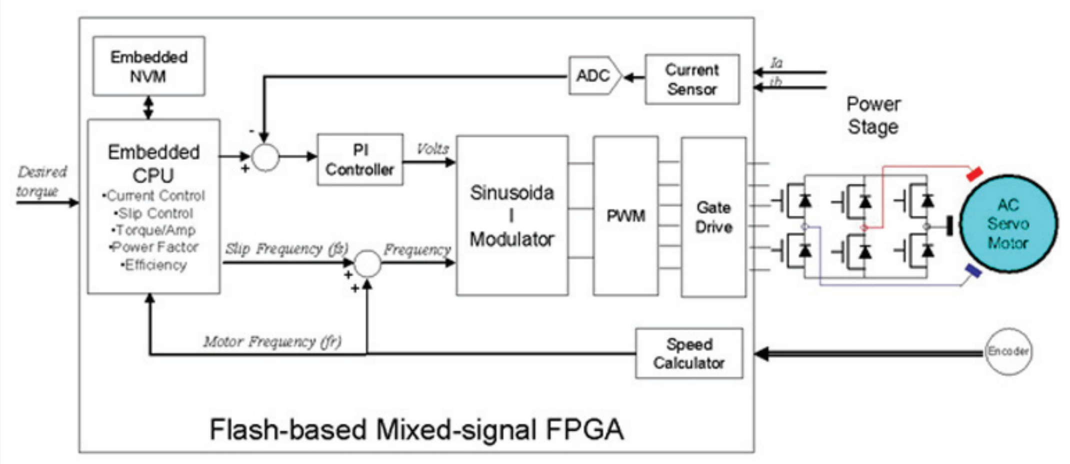

Figure 3: Mixed-Signal FPGA implementation for slip control.

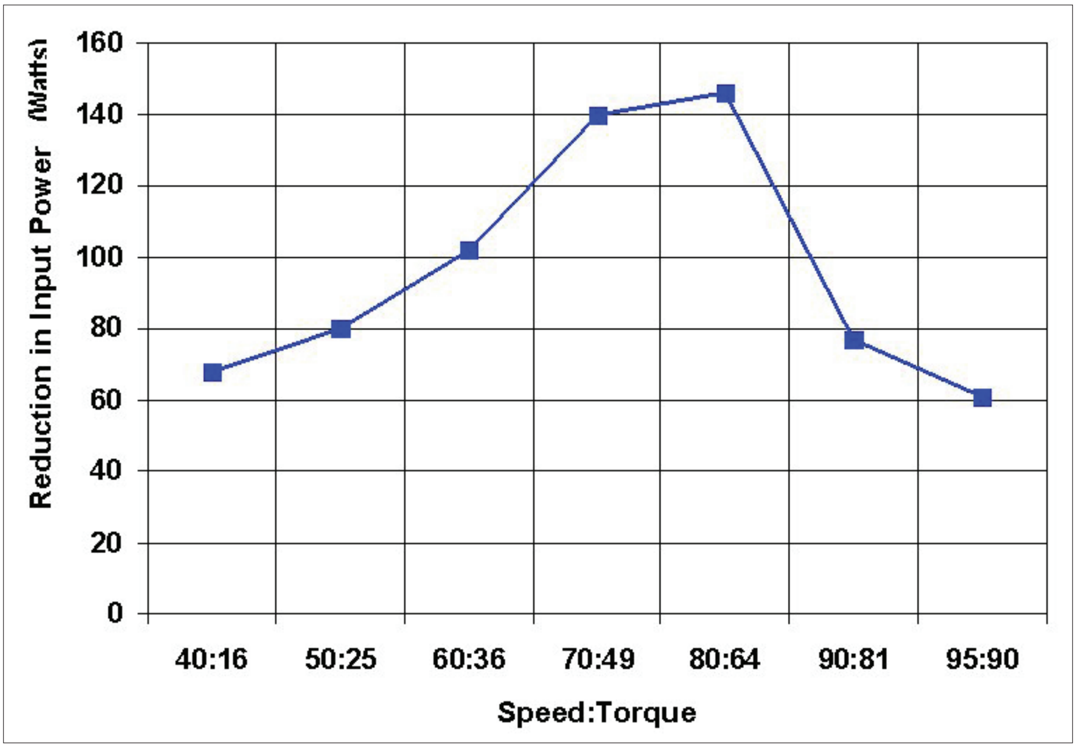

Figure 4: Power reduction due to slip sontrol compensation (Input Power = 8477 W).

Determining a method for efficient slip control in AC motor control is critical, particularly for industrial automation applications that require heavy load operation.

AC induction motor control algorithms

There are two basic AC motor control algorithms: speed control and torque control. The slip control algorithm targets torque control, which is achieved by controlling both the phase current and the slip frequency (**Figure 2**). The voltage is adjusted by the PWM to maintain the desired slip frequency. In order to provide optimal performance in slip control, current and speed feedback from the motor prompts the software to compensate for variable conditions. Rate of sense sampling and calculation bottlenecks reduce the response to changes in speed and current and therefore limit the responsiveness and efficiency of the system.

The desired torque value is fed into the example system above. With a fixed slip frequency, torque is increased by increasing the current. Similarly, with a constant current increasing slip frequency will increase torque. Current and slip LUTs are implemented in the system to provide fixed value responses to each current or slip sensed value in order to provide the appropriate voltage response based on the desired torque.

The torque/slip curves are dependent on the motor. Therefore, the slip LUT needs to be customised for the motor. The slip control algorithm is not difficult to implement; however, generating the slip tables may not be straightforward. The difficulty is determining the value of slip for a given current. Since maximum motor efficiency does not occur at maximum torque, it is tempting to choose low slip frequencies to maximise motor efficiency. However, since the controller's power loss is related to current, it may be more beneficial to lean towards a maximum torque per ampere. In either case, the torque profile should be tailored to the application.

The parameters of torque/slip curves in this LUT are highly user-specific and motor-dependent. The table is usually implemented in flash memory for MCU access. The local bus bandwidth, flash memory look up time and MCU speed determine system performance.

Slip optimisation

Optimised control of the induction motor can be achieved by directly controlling the slip value or slip frequency. For each induction motor there is a profile like the example shown in Figure 1. There are distinct slip values for maximum torque (breakdown point), maximum power factor, and maximum motor efficiency. Typically, the rated slip (rated torque) of the motor falls somewhere between the maximum power factor and maximum efficiency.

The slip frequency (supply frequency needed to achieve the desired slip) can be controlled in a variety of ways. In such a system, a speed sensor is used to measure rotor frequency and the supply frequency is determined by targeting a desired slip value. The target slip value will depend on the application or system needs. For example, an application concerned with system efficiency could ensure that the slip frequency is maintained to maximise efficiency.

Processor-based systems

AC induction motors can use processor-based implementations such as PIC MCUs from Microchip or MC68H MCUs from Freescale Semiconductor. These processors include on-board flash for LUTs, ADC and PWM outputs. As discussed above, the bottle neck in this type of system is created through processing time for the control algorithm, LUT rates and bus speed.

Mixed-signal FPGA systems The system shown in the **Figure 3** is implemented in Actel's mixed-signal Fusion FPGA. The device contains nonvolatile memory (flash memory); integrated analogue, including analogue blocks, an analogue-to-digital controller (ADC) with multiple analogue I/Os; and, in some cases, an embedded CPU.

Tight control loop

This single-chip system with both CPU- and FPGA-based processing power allows tightening of the entire control loop. The on-chip CPU is able to respond to the feedback frequency as well as phase current, and to access the on-chip parameter LUT immediately. The external memory bus bandwidth bottleneck is eliminated in the first stage.

Moreover, the flash-based, mixed-signal FPGA is able to optimise the control algorithm blocks, proportional integral (PI) controller, speed decoder and calculator, and sinusoidal modulator with FPGA logic gates, instead of software routings executed by MCU or DSP processor. The response time and efficiency improvements are achieved in the second stage.

Finally, the on-chip ADC with multiple analogue channels (up to 30), voltage/current/temperature inputs and MOSFET gate drive outputs, are able to reduce the acquisition and process time of multiple phase current and temperature data significantly. The mixed-signal FPGA has built-in circuitry for current, voltage and temperature monitoring, which reduces components normally implemented external to the MCU.

High integration

AC induction motors are widely deployed on the manufacturing floor. Noise is always the critical issue that impacts the performance of industrial automation equipment. In addition to high-speed analogue and digital data transfer on the control plane, numbers of discrete electronic components increase noise impact. Integration is therefore a critical factor in the choice of solutions to avoid noise impact and improve reliability.

Efficient control

According to the United States Environmental Protection Agency, the use of systems with efficient slip control mechanisms can provide significant power savings in typical AC motors. **Figure 4** shows an example of power saving due to slip control compensation in a 10-horsepower (HP) motor (Input Power = 8477 W).

In this example, if the slip control is used to keep the motor operating in the optimal zone where maximum reduction in input power exists at about 145 W, a reduction in source power of 1.7 per cent can be achieved. In 2005, AC induction motors used around 100,000 crore (1,000 billion) kW in the United States alone. A total power saving reaching 1710 crore (17.1 billion) kW can be achieved with the use of optimised slip control.

In the power stage, with the above efficiency enhancements in slip control, AC motor horsepower will be increased accordingly. This means lower supplied power can deliver the same horsepower performance. Thus, reduction of power consumption becomes the major benefit.

In the control unit designed to achieve improved slip control, a lower-speed CPU, with peripheral modules implemented in logic gates, can have superior performance to a very powerful stand-alone CPU. The inherent low-power technology and single-chip solution offered by mixed-signal, flash-based FPGAs further reduce power consumption in the system.

Embedded nonvolatile memory

The parameters used by the control algorithm are dependent on motor types and specific applications, and are usually implemented in a flash memory LUT. These parameters are the key reference data for MCU to access and update when operating and improving efficiency of the motor. Security of this data is required to protect the control parameter from being erased or hacked accidentally or maliciously, potentially causing damage to the motor itself.

The mixed-signal FPGA that has a large amount of embedded NVM which is secure against accidents created by noise, firm error, and power loss. Higher level security can be implemented with the AES decryption feature, which allows for secure update of embedded flash memory blocks, and prevents malicious attacks.

Soft start induction motors When an induction motor is started, the slip value is equal to 1 since the rotor is not moving. Therefore, the induced magnetic field and current in the rotor can be very large. This in turn causes a high current to be drawn by the stator that can cause damage to the motor if not controlled. Using a mixed-signal FPGA with built-in voltage and current monitoring capability to provide ramp rate control, the motor can be soft started to prevent any possible damage to the motor.