Motor Efficiency Depends Upon Power Factor

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Overview

Electric motor power efficiency has taken center stage. Individuals, corporations, and governments are increasingly interested in saving power, now that technology can make it possible and economy demands it. Advances in motor control algorithms and cost-effective electronic components for implementing motor drives are creating a revolution in virtually every electric motor market. Control of the power factor in an efficient manner also means less lost energy, both in the motor and drive electronics, and in the power grids supplying the electricity to the homes, offices, and factories where the motors are used.

Potential Savings

The potential energy savings are staggering. Over 40 million electric motors are used in manufacturing operations in the United States alone.[1] Electric motors account for 65 to 70 percent of industrial electrical energy consumption and approximately 57 percent of all electrical consumption worldwide.[2] Saving even a few percent of the world's estimated 16,000-plus terawatt-hours (TWh) annual consumption of electricity[3] amounts to several hundreds of trillions of watt-hours per year. Currently, the average motor in use today has an efficiency of 88 percent in converting electrical into mechanical energy. Figures on the order of 96 percent conversion efficiency are technically feasible for larger motors.

For comparison, the electrical generation capacity of photovoltaic solar cells in all of Europe, where both Germany and Spain currently lead the US in installed base, is projected to be only 15 TWh/yr in 2010.[4] In the UK alone, with an annual total electrical consumption of approximately 350 TWh, the Institute of Engineering and Technology estimated that 5 TWh could be saved annually through the use of more efficient electric motors.[5] Furthermore, many motors are not used in an efficient manner. For example, the motor may be oversized for the job at hand, or much of its mechanical output power may be wasted, meaning that additional savings may come from how the motor is used, on top of the savings from the motor itself. In 1996, the United States Department of Energy speculated on savings of 5 TWh per year by 2000, and a 100 TWh per year savings potential by 2010,[6] considering both motor and related system-level savings.

The potential is there to make significant advances in the next few years as older motors and drives are replaced by newer more efficient ones. Because of the cost savings in electricity, many industries are voluntarily accelerating the turnover of their installed motor base, even replacing motors before they wear out. This is because the payback for the newer, more efficient motors and drives can be realized in less than a year and usually less than two years. Great strides are already being made. In the UK, for instance, sales of the least efficient motors, grade Eff3, have dropped from 68 to 8 percent between 1997 and 2004. During the same period, sales of the most efficient grade (Eff1) have increased from 2 to 7 percent,[7] and further jumped to 17 percent in 2006,[8] with the middle grade (Eff2) making up the balance of sales.

Regulatory Influences on Motor Efficiency

Governments around the world are providing regulatory pressure to use more efficient motors. Starting with the Environmental Protection Act of 1992, which mandated motor efficiency standards and took effect in 1997, the United States government has been steadily increasing regulations.There are other voluntary incentives as well, such as National Electrical Manufacturers Association's (NEMA) Premium® efficiency labeling standard (2001). Australia implemented standards on motors ranging from 0.73 KW to 185 KW in 2001 and tightened efficiency requirements in 2006. Very recently (March 2009), the European Union passed mandatory Minimum Efficiency Performance Standards (MEPS), which will be phased in from 2011 to 2017. Brazil (2002) and China (starting in 2010) also have current or planned mandatory standards. See Figure 1 on page 4 for a comparison of efficiency requirements for various-sized motors in several jurisdictions, including the voluntary NEMA and Consortium for Energy Efficiency (CEE) standards, versus the wide range of efficiencies of available motors.[9,10] The lines depict several mandatory and voluntary world-wide motor efficiency standards and the highlighted area represents commercially available motors.

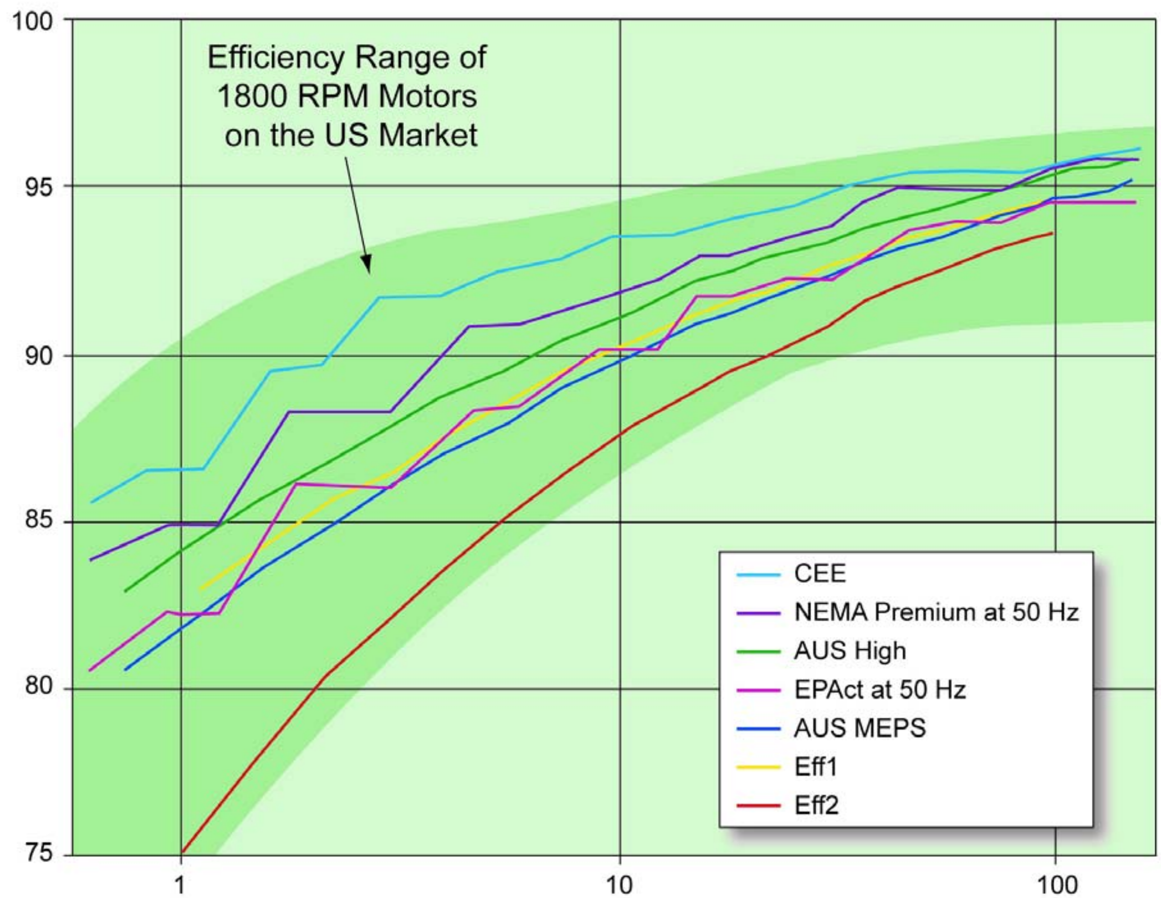

Figure 1: **Efficiency Range of 1800 RPM Motors**

Motor Controllers

Electric motor savings are achieved in several ways. The first is in the motor design itself, through the use of better materials, design, and construction.

Another is by optimizing the mechanical angle between the various rotating magnetic fields inside the motor. This is done using the newer family of motor control algorithms, generally referred to together as space vector control, flux vector control, or field-oriented control. By keeping the magnetic fields of the rotor and stator oriented with the optimal angles between them under various speed and torque conditions (typically near 90 degrees), the motor can always be operated at peak efficiency. As a side benefit, other characteristics can also be optimized, such as fast and stable dynamic response to load changes, precise control of speed or torque, soft starting and braking, prevention of stalling at low speeds, high starting torques, and fault detection; often without sacrificing much in the way of overall energy efficiency. Some of these features were once obtainable only from a more expensive motor type, but can be achieved with the now ubiquitous, low-cost, and reliable AC induction motor, which comprises 90 percent of U.S. motor sales. One of the most significant advantages of the newer control algorithms is efficient variable speed operation.

A very large opportunity for system-level energy savings comes from using variable speed motor drives. A well-designed pump or fan motor running at half the speed consumes only one-eighth the energy compared to running at full speed. Many older pump and fan installations used fixed-speed motors connected directly to the power mains, and controlled the liquid or air flow using throttling valves or air dampers. The valves or dampers create a back pressure, reducing the flow, but at the expense of efficiency. This is probably how the HVAC forced-air system works in your office building; dampers control the airflow into each workspace while the central fan, which is sized for peak requirements, runs at full speed all the time—even if the combined airflow requirements of the building are currently very low. Replacing these motors with variable speed drives and eliminating or controlling the dampers more intelligently can save up to two-thirds their overall energy consumption.[11]

Power Factor

One often overlooked aspect of overall motor drive efficiency is the power factor. The power factor relates the shape of the current waveform drawn by a load to the sinusoidal voltage waveform supplied by the power company. If a load looks purely resistive, then the current drawn by the load is a sinusoid exactly in phase with the voltage waveform, and the power factor is unity (1). This is the most efficient condition.

If the load appears to be inductive, as it does in many motors, the current will lag behind the voltage in phase, and the power factor will be less than one, according to the cosine of the phase angle. Capacitive loads, which cause the current to lead the voltage, also reduce the power factor below one. In either case, the energy supplied to the motor will not be used optimally. Since the peak (and shape) of the current sine wave does not line up with the peak of the voltage sine wave, the instantaneous product of voltage times current averaged over a full cycle is lower. This is called the true power and is measured in watts.

Figure 2 is a vector diagram showing the relationship of apparent power to true (useful) power.

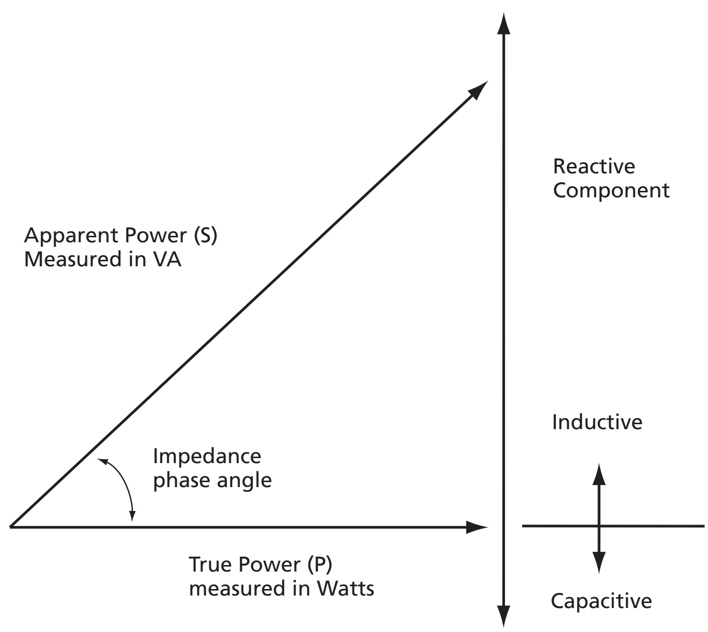

Figure 2: **The Power Triangle**

Since the mains voltage is fixed, a higher current is required from the power company to compensate for the phase shift and deliver the same usable power to the motor, bringing the usable power (in watts) back up to the level required to do the desired mechanical work (in horsepower, for example).The product of this higher RMS current and the RMS voltage (measured in volt-amps) is called the apparent power. In many respects the power company has to build the infrastructure and pay for the higher apparent power, even though only the true power is doing useful work for the end user. This higher current means more losses as the power company generates and distributes the power. Power-line transformers can heat up and fail. Power losses go up as the square of the apparent power. A power factor of 0.7 means an apparent power of 1.4 times the true power, with nearly double the losses compared to a power factor of one.

Higher capacity circuit breakers will be needed on the branch circuit where the motor is used. Voltage drops on power distribution wiring will as much as double, necessitating an even higher current for the same delivered power. There are higher resistive losses in the motor as well, creating more heat and a shorter motor life. Alternatively, heavier wire must be used for the windings, reducing the number of turns and hence the efficiency of the motor. The reactive component of the current, which is out of phase with the voltage, is accomplishing no useful work, yet it creates additional losses in the overall system above and beyond those of the in-phase component that is doing all the real work.

In cases where inductive or capacitive loads are linear, the power factor is often expressed as the true power divided by the apparent power.

Because of the extra capital and operating costs imposed upon them, it is very common in industrial settings for power companies to add surcharges for power factors below 0.95, though this is rarer in residential settings where the price of power reflects average residential power factors and the associated costs.

Why Worry About Power Factor?

In an industrial setting, you can reduce your electrical bill by cutting power factor surcharges from the power company.

You will be able to put more true load on your branch circuit, since reduced reactive load currents will flow through your circuit-breaker junction box. Efficiency-sapping voltage drops in your branch circuits may also be reduced.

Finally, you might be required to worry about power factor by government regulations. European countries require power factor correction for power supplies rated over 75 W (IEC 555) and limit the harmonic distortion a power supply can inject into the mains though IEC/EN61000-3-2. These regulations require controlling the input current distortion up to the 40^{th} harmonic of the line frequency.

Combating Low Power Factor

Fixed-speed AC induction motors connected directly to the mains voltage look primarily inductive from the point of view of the power plant and distribution grid. To combat the inefficiency this causes (and the corresponding surcharges from the power company), industrial concerns will often add a compensating capacitive load to the power line. This shifts the phase of the power line current so it is back in phase with the voltage. Since the added capacitive load is mainly reactive, it dissipates almost no power itself, except due to non-idealities such as non-zero series resistance and leakage.

Fixed-value capacitors can be applied or removed automatically by a centralized power factor controller, based upon measurements of reactive currents as factory motors are turned on and off. Another scheme is to use an unloaded motor-generator as a sort of synthetic capacitor called a synchronous condenser; usually one such machine for a whole factory full of motors. The closer the compensation capacitors are to the motor(s), the better, as there are still reactive currents flowing back and forth between the inductive and capacitive reactive loads. Note that the current component supplied by the power company can be made to look almost purely resistive with the right compensation, localizing the reactive part of the load current so it does not have to go over the long transmission lines from the power company to the factory—and this also keeps it off your electric bill.

Power Factor Correction for Modern Motor Drives

While modern motor drives provide many features and can greatly enhance the efficiency of the motor itself, and can often make the whole system containing the motor more efficient with new features such as variable speed control, there is at least one downside of the new technology. Everything you have learned about correcting the inductive power factor of electric motors using capacitors is irrelevant.

The bad news is that simple capacitive power factor correction schemes used in the past do not work well for modern motor drives. With the new generation of motor controllers, the motor drive electronics look like a large AC-to-DC power supply when viewed from the power grid. Without power factor correction, these look highly non-linear. A quick look at a motor drive block diagram reveals why. Motor drive electronics usually consists of two main parts: a rectifier that converts the AC input mains voltage to an intermediate DC power bus and an inverter that converts the DC bus voltage to AC at the motor's operating frequency and current. In many ways, these two main blocks are duals: one efficiently converts AC-to-DC, and the other efficiently converts DC-to-AC. The energy losses in these two blocks, though they may seem a roundabout way to go from AC to AC, are more than offset by the efficiencies gained in having more control over the magnetic field phase and the added advantage of variable speed operation.

Figure 3 shows a modern motor drive, consisting of an AC-to-DC rectifier followed by a DC-to-AC inverter.

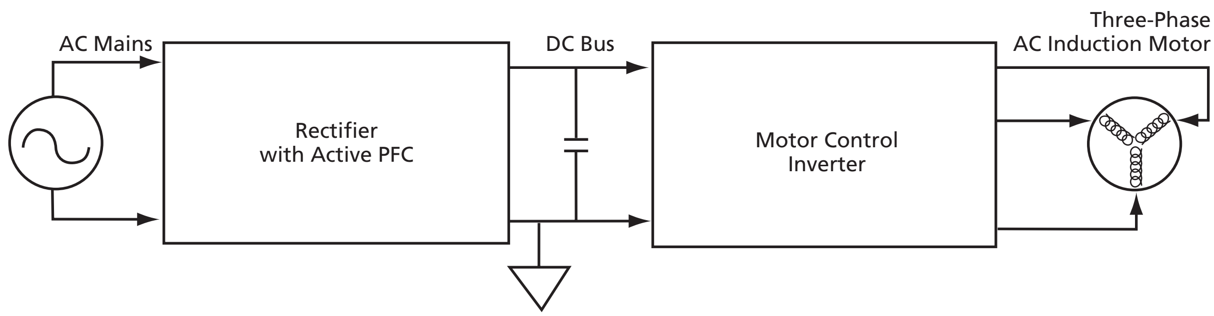

Figure 3: **Modern Motor Drive**

Nearly all single-phase AC-to-DC power supplies have a full-wave bridge rectifier circuit on the input, followed by a large bulk capacitor, which attempts to hold its DC voltage constant between the half-cycle peaks of the input voltage sine wave. Of course, no matter how large it is, the capacitor droops slightly between half-cycles, so when the next peak comes, the rectifier bridge conducts and recharges the capacitor.The capacitor charging current only flows when the input voltage (less the voltage drops across the rectifiers) is greater than the voltage on the capacitor; when it is less, the rectifiers are off and little or no current flows. Therefore, the current is highly non-sinusoidal, as shown in Figure 4 on page 8. The low power factor caused by the high harmonic content of the currents causes problems for the power company that are similar to those caused by sinusoidal reactive power—only worse. The harmonics cause distortion in the voltage waveform, and can even cause destructive resonances in the power grid.

Figure 4 shows that a simple rectifier without power factor correction (PFC) draws current from the AC mains with a high harmonic content, and hence a low power factor.

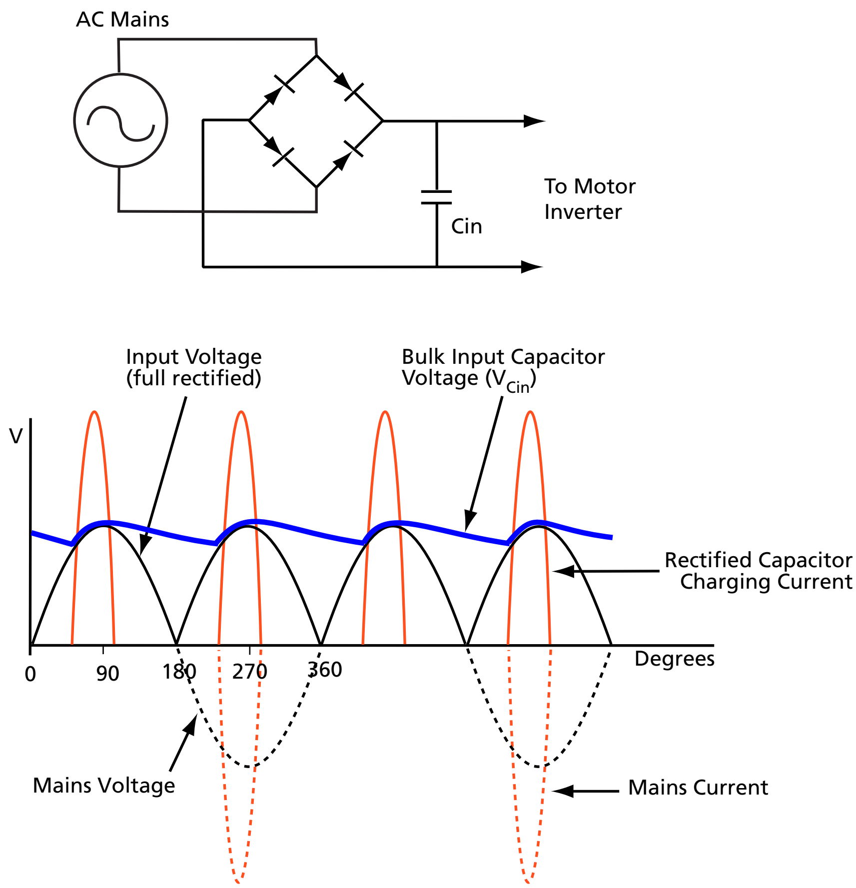

Figure 4: **Simple Rectifier without Power Factor Correction**

Uncorrected power factors may be as low as 0.5 or 0.6 for this type of rectifier design. A similar situation applies to three-phase mains power, but the rectifier bridge has six diodes instead of four, and the phase peaks six times per cycle instead of twice.

For lower power systems (<100 W), passive power factor correction (PFC) can be used. For these low-power applications, the energy efficiency of passive PFC can be relatively high (for example, 96 percent efficiency). A low-pass filter, usually comprised of an inductor, capacitor, and resistor, is inserted between the AC mains input and the bridge rectifier. This tends to draw most of the current out of the mains at the line frequency, which is within the passband of the filter. The harmonics of the line frequency are reduced to some degree, and the current waveform is smoothed out. Passive power correction is generally not sufficient for motor control applications due to its marginal performance with respect to the resulting power factor (typically around 0.75), and the large size of the components for higher power applications.

Active Power Factor Correction

Active power factor correction can achieve very high power factors—0.98 and above—with reasonably sized components, though the energy efficiency may be slightly lower than with passive techniques (94 percent compared to 96 percent, for example) due to the addition of switching components.

In one of the simplest architectures, an inductor, a metal oxide semiconductor field-effect transistor (MOSFET) or insulated gate bipolar transistor (IGBT) switch, and a diode are added between the rectifier bridge and the bulk capacitor, in a boost switch-mode power supply configuration. Figure 5 shows an improved rectifier with active power factor correction (PFC), which draws current from the AC mains exactly in-phase with the mains voltage, for a high power factor.

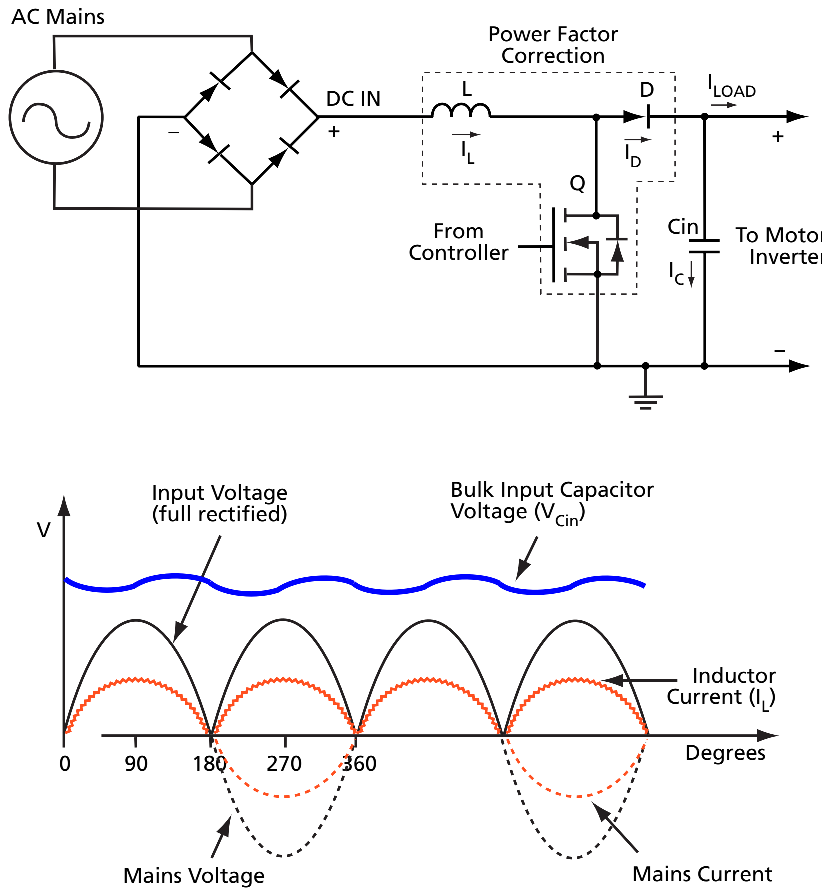

Figure 5: **Improved Rectifier with Active Power Factor Correction**

This is how the AC-to-DC boost converter works: The intermediate DC bus voltage is chosen to be higher than the peak voltage of the rectifier bridge, so the switch-mode controller will be working in boost mode. The controller driving the switch (Q) will adjust the duty factor of the switch control signal so that the desired current and voltage targets are maintained. The switching frequency is chosen to be much higher than the AC mains frequency (60 Hz compared to 20 KHz, for example). The small current ripple at the switching frequency and its harmonics can be filtered using a passive filter on the AC mains input, similar to passive PFC, but much easier because of the lower amplitude and higher frequency of the ripple current.

During phase one the switch is closed, shorting one end of the inductor (L) to ground. Current is drawn through the inductor via the rectifier bridge, energizing the inductor's magnetic field. During phase two, the switch is open. Since the current on the inductor cannot change instantaneously, the voltage on the inductor increases almost instantaneously until it is above the DC bus voltage by enough to turn on the diode (D). The current going through the inductor charges the bulk capacitor (C) as the magnetic field collapses slightly and simultaneously raising the DC bus voltage slightly. All the while, the motor inverter is drawing current from the DC bus in order to power the motor, using up the charge stored on the bulk capacitor and thus reducing the DC bus voltage.

The amount of current drawn out of the AC mains is controlled in a manner such that the short-term average current is in phase with the mains voltage sine wave. Thus, the current through the inductor is controlled so that it approximates a full-wave rectified sine wave, plus and minus the switching frequency components. The average amplitude of the full-wave rectified current is controlled over the long term so that the DC bus voltage is regulated to the target voltage. This means the average current flowing into the capacitor from the rectifier and inductor (when the transistor switch is off) must match the average current going out to the inverter and motor.

Rectifier (with PFC) Efficiency

The boost configuration switch-mode regulator with power factor correction can be very efficient. Even though the input current is shunted to ground during phase one, little energy is lost because the voltage drop across the low-impedance switch is small. Most of the energy goes to build up the magnetic field of the inductor, and this energy is recovered and transferred to the bulk capacitor during phase two.

There are small voltage drops across the diodes in the system, but these are proportionately fairly low for high-voltage circuits. If they become a concern, the diodes can be replaced with low-impedance MOSFETs or IGBTs with lower ON voltages than the diodes they replace. These are switched at the appropriate times by the controller—when the voltage across them goes through zero, the way an ideal diode would switch. There are small energy losses during the switching intervals when the switch transistor is not ON enough to have a low voltage, and not OFF enough to have a low current; so for a brief instant during each transition there are $I^2 \cdot R$ losses in the switch transistor. Also each cycle there are $C \cdot V^2$ dynamic energy losses caused by charging and discharging the gate capacitance of the transistor. The inductor can have $I^2 \cdot R$ losses due to the DC resistance of its windings. Often, coreless toroidal inductor designs are used to minimize dynamic core losses and allow for higher currents without saturation problems. Finally, the bulk capacitor must have low series resistance and must be reliable under conditions of large switching currents. All these potential losses must be considered and mitigated by careful design and component selection, as in any switch-mode power supply design.

Adding Options

The basic active power factor correction architecture, shown in Figure 5, can be enhanced in a number of ways. One way is to adapt it for three-phase AC mains input power.

A simple full-wave rectifier for three-phase inputs consists of six rectifier diodes instead of the four in the single phase bridge. Unfortunately, it is difficult to achieve a good power factor using just diodes, because they only conduct for the half-wave output with the highest instantaneous voltage. For a good power factor, there must be half-wave sinusoidal currents being drawn or returned through all six branches of the input bridge in the correct phase relationship. One way of solving this dilemma is by using switching transistors in place of the six diodes and controlling them with a pulse-width-modulation (PWM) controller that ensures current is being drawn from each phase, over a short-term average, in direct proportion to the phase's voltage. As before, the long-term average current is determined by the needs of the motor.

Another enhancement to the whole rectifier/inverter system is to provide for dynamic motor braking, or regeneration. In this mode, the motor inverter sends current from the motor, which is acting in a generator mode, back into the bulk storage capacitor, raising the DC bus voltage. One simple way to prevent the DC bus voltage from going out of regulation is to dump the excess current into a resistive load using another simple PWM controller. Depending upon how much momentum is attached to the motor, the amount of energy dumped can be very substantial. This energy is forever lost, and can generate a great deal of heat.

A more sophisticated solution is to modify the rectifier so that it can return the energy to the AC mains. Instead of drawing current out of the mains in phase with the voltage of each phase, the rectifier controller returns current to the power company by inverting the phase of the current so it is exactly out-of-phase with the input voltage. Even though the current is inverted, it must still have a good power factor in order to be useful. The current should be sinusoidal, exactly out-of-phase (not reactive), and have low harmonics; in other words, it must be like the current that would flow if the load were an ideal negative resistor. With these conditions met, the sinusoidal out-of-phase current supplied to the mains during braking can be used by some other device in the factory that is consuming in-phase current, reducing the net local power consumption. If there is no other load to use the power locally, the power meter will run backwards as the energy is returned to the power company, where someone else can use it, thus reducing the load on the main generators.

Note that when designed to do dynamic braking with three-phase AC mains, the rectifier looks almost like an inverter. It is really supporting both modes: power flowing from the AC mains to the DC bus (rectifier mode), and power flowing from the DC bus back to the AC mains (generator, or inverter mode).

The simple boost mode switcher presented earlier cannot do all these jobs. Conversely, more complex architectures, such as the Ćuk-Ćuk boost-buck three-phase rectifier with regenerative capability (Figure 6) can do all these jobs and more.[12]

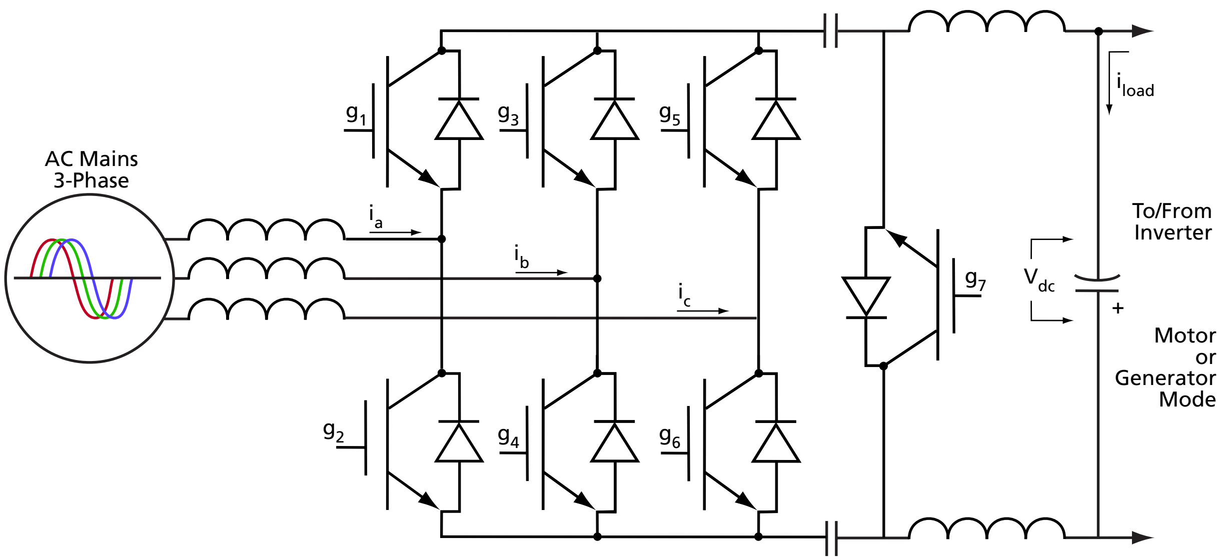

Figure 6: **Ćuk-Ćuk Boost-Buck Three-Phase Rectifier Architecture**

Another enhancement is for one large rectifier to supply DC power to multiple loads, possibly including several inverters driving AC induction motors, in what is called multi-drive operation.[13] In the debate started over a century ago between Thomas Edison and Nikola Tesla about the relative benefits of AC and DC power, Tesla (who favored AC) may have ruled with the technology available in the 20th century, but Edison might win in the 21st. More likely, both will coexist, with DC power having a much greater role than in the past.

Control Algorithms

Space does not permit a thorough review of either motor control or power factor correction algorithms. One significant observation is that many of the same concepts and algorithms being used in modern motor control have a dual in rectifier control. Terms such as sensorless, observer, space vector control, and dq-to-abc transform abound in the literature of both fields.

This translates into creating implementations that require the same types of computational elements, and of approximately the same complexity—at least for the high-end systems—for both motor inverters and rectifiers with power factor correction.

Figure 7 is a block diagram of a controller that uses load feed-forward to provide faster response to load changes than can be obtained by monitoring the DC bus voltage alone, including possible sudden changes from driving the motor to dynamic braking. The abc-to-dq and $e^{-j\omega e}$ block, and the $e^{-j\omega e}$ and dq-to-abc block, transform back and forth between a rotating three-phase frame of reference synchronous with the AC mains voltage, and the stationary orthogonal frame where the proportional-integral (PI) control laws are applied. The pulse wide modulator (PWM) drives the gates of the seven switching transistors in the Ćuk-Ćuk rectifier.

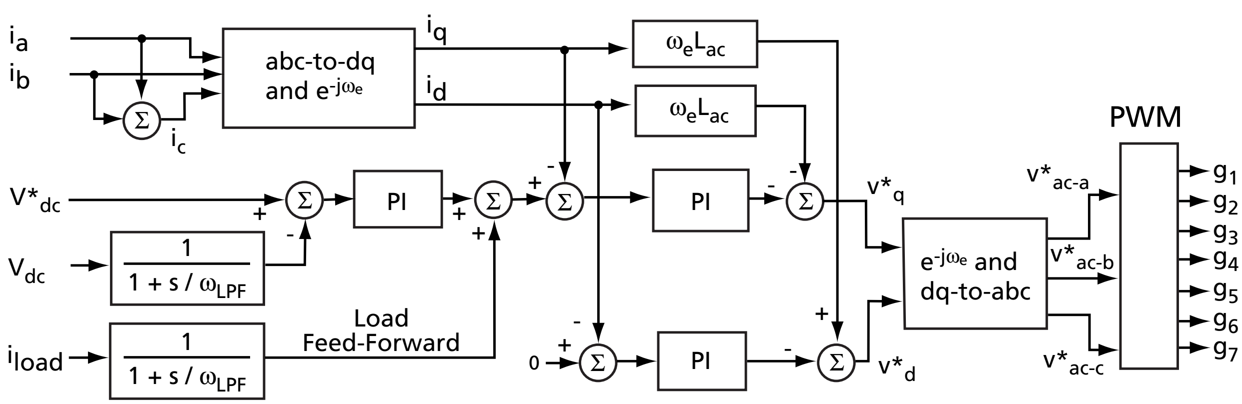

Figure 7: **Simplified Block Diagram of a Ćuk-Ćuk Boost-Buck Three-Phase Rectifier Control Algorithm**

Implementing a Controller

Simple active power factor correction, like simple motor control, can be implemented inexpensively in a number of ways. One of the most common is using a low-end microcontroller. This would be sufficient for DC motors and stepper motors on the motor side, or a simple single-phase boost regulator on the rectifier side. Several companies offer mixed-signal application specific standard products (ASSPs) capable of solving some specific power factor correction problems.

Mid-range systems, such as controlling a single motor at a modest sampling frequency, can be implemented using one of the many digital signal processor (DSP) microcontrollers designed for motor control applications. These often have special functions integrated on-chip to support motor control, such as support for current sensing, comparators, and dedicated PWM peripherals. It should be possible to adapt these products to mid-range rectifiers, as well.

Things get more interesting when there are special requirements. Then, DSP microcontrollers may run out of steam. Most DSPs are flexible, but inherently they are sequential state machines that can only do a very limited amount of computation in a single clock cycle. As algorithms become more complex, sampling frequencies rise, and higher levels of integration are desired, the DSP solution either fails altogether, or becomes too expensive.

In that case, the ideal solution is a mixed-signal FPGA. These offer many of the special analog functions (such as current sensing) needed for either of the motor control or rectifier problems, plus a configurable logic fabric. Unlike DSPs, the mixed-signal FPGA can do many computations in parallel, and can do certain specialized computations such as computing sines and cosines (which are generally required by these algorithms) much faster than most any DSP microcontroller, at a lower cost per computation.[14] As a bonus, FPGAs invariably consume less power than any type of microcontroller doing the same function.

This is because only a small part of most microcontrollers is dedicated to doing computations; most of the energy is being used to move data from place to place, fetch the next instruction, and the like.

Mixed-signal FPGAs combine the best features from both worlds: a software-driven microcontroller in either soft gates or hard gates (loaded in the FPGA fabric, or built into the FPGA itself) can be combined with logic dedicated to some aspect of the controller problem and loaded into the FPGA fabric.

The following quote is from the BDTi website. BDTi performs various performance and power benchmarks of DSPs and FPGAs.

> *Another interesting aspect of FPGA flexibility is that FPGAs can readily incorporate processors, but DSPs, GPPs, ASICs, and ASSPs cannot readily incorporate configurable logic. In BDTI's consulting practice we are often called upon to help system developers select chips for their next-generation products. In many cases the previous design incorporates a DSP and an FPGA. In some cases, this combination will continue to be appropriate for the next-generation design. But in other cases, there may be strong incentives to consolidate. In these cases, it is more likely that the FPGA will be able to subsume the functionality handled by the DSP than the reverse. This dynamic favors increased adoption of FPGAs.*[15]

FPGAs offer much flexibility. For instance, if your algorithm requires an extra PWM, it can easily be added to an FPGA solution. PWMs pre-built into a DSP or ASSP integrated circuit may or may not perform the PWM algorithm you want, or take into consideration the needs of your power circuitry. With an FPGA, the PWM can be customized exactly to your specifications. An FPGA can be adapted to accept most any type of feedback sensor (encoder, Hall effect, or tachometer, for example); or a sensor-less algorithm based upon motor back-EMF measurements can be implemented.

Great opportunities for increased integration lie with mixed-signal FPGAs. Probably the most intriguing example is to incorporate nearly all the control functions for both a high power factor rectifier and a motor control inverter in a single device, including many of the analog functions. Another common application would be to have more than one motor controller implemented in a single chip, for multi-axis applications. This is an ideal application for multi-drive, with one rectifier supplying two or more motor inverters. A mixed-signal FPGA-based solution can achieve higher sampling rates for high-dynamic or high precision applications.

Summary

There is tremendous potential for worldwide energy savings in the current trend to upgrade electric motors and motor controllers. An often overlooked aspect is that active power factor correction is virtually a requirement in modern motor drives due to the highly non-linear load they would present to the AC mains without it. Regulations in many countries are not only demanding more efficient motors, but also improved power factor correction and reduced harmonic currents.

While low- and mid-range applications can be reasonably well served with existing general-purpose microcontrollers, DSPs, and ASSPs, the desire for more advanced algorithms, higher sampling frequencies, and higher levels of integration are straining these solutions beyond their capabilities. Mixed-signal FPGAs have the correct attributes to satisfy the needs of advanced applications.

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United Kingdom
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1-24-14 Ebisu Shibuya-ku
Tokyo 150 Japan
Phone +81.03.3445.7671
Fax +81.03.3445.7668
http://jp.actel.com

Actel Hong Kong
Room 2107, China Resources Building
26 Harbour Road
Wanchai, Hong Kong
Phone +852 2185 6460
Fax +852 2185 6488
www.actel.com.cn

55900100-0/6.09