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Motion Control Engine Achieves High Efficiency with Digital PFC Integration in Air Conditioner Applications

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As presented to the ISEE Conference, San Francisco, May 2006

***Abstract*— Permanent magnet motors are commonly used in AC inverter controlled air conditioner systems for home appliances. Acoustic noise and vibration reduction in the outdoor unit compressor is an important task, in addition to attaining high efficiency power usage. It is also required to eliminate motor position sensors such as Hall Effect sensors due to the structural constraint of sealed compressors. These requirements naturally lead manufacturers to incorporate sinusoidal sensor-less PM motor control.**

Today, most air conditioner units are based on 32 bit RISC microcontrollers to achieve compressor motor control. In outdoor unit air conditioners, not only does the compressor use an AC inverter but also the fan uses an AC inverter. The fan is also based on a PM motor and its control is based on Hall Effect sensors in today's system. Power factor control is also required for a certain power range of air conditioner, which has normally been implemented by separate analog PFC control IC.

This paper discusses a hardware computation-based dedicated controller for air conditioner applications that enables sinusoidal sensor-less PM motor control for both compressor and fan, and digital PFC within a single monolithic silicon platform. Sensorless Field Oriented Control (FOC) is implemented using an embedded Motion Control Engine (MCE) so that computation power can be attained with two motor FOC controls and digital PFC combined.

Air Conditioning control Systems; Sensorless PMSM control; Motion Control Engine; Integrated Design Platform

I. INTRODUCTION

Air conditioning systems are typically the largest consumers of electrical energy in homes and office buildings. The number of homes with air conditioning has been steadily rising over the past 25 years and now more than 75% of US households have either central or room air conditioning systems [1]. The average air conditioning unit's efficiency has also been improving and so even though the number of households with air conditioning increased by 70% between 1978 and 1997, the total electricity consumed for cooling increased by only 35%. There is still a significant amount of energy consumed for cooling and in 2001 over 180billion kWhr of electricity was used for air-conditioning, accounting for about 16% of the total residential energy consumption and about 5% of the total US electricity consumption [2].

Further improvements in efficiency are needed not only to conserve energy resources but also to reduce emissions of 'green house' gasses and other pollutants since over 70% of US electricity is generated by burning fossil fuels and nearly 50% generated by burning coal [3]. In January 2006, new regulations came into effect increasing the minimum SEER (Seasonal Energy Efficiency Rating) from 10 to 13 for US conditioning systems, which will lead to a 25% reduction in the air conditioning load. This saving is significant not only for the total energy used but also because it reduces the generation capacity required for the peak summer load. If we assume an average cooling capacity of 8.8kW (30,000BTU) for the 80m households using air conditioning then the peak air conditioning load with an average SEER of 10 is 240,000MW requiring about 240 very large coal or nuclear power plants. A 25% energy saving could eliminate the need to build 60 large and expensive power generation plants.

Japan has been leading the way in energy conservation for many years especially since the energy crisis of the 1970's when over 77% of Japan's energy supplies came from imported oil [4]. Over the past thirty or more years this dependency has been reduced to about 50% but energy conservation across all sectors is still a major priority. There have also been significant improvements in appliance efficiency that has helped to keep Japan's ratio of GPD to energy consumption significantly less than that of the major developed nations and, in fact, more than two and a half times lower than the US number. This has been achieved through higher consumer electricity pricing (more than twice that in the US) and by setting energy conservation standards for home appliance manufacturers. For example, the average energy consumption used in cooling for a 2.8kW capacity air conditioner has fallen from 363kWhr in the 1995 model year to 202kWhr in the 2004 model year [5].

These efficiency gains have been achieved through improvements in air conditioning system mechanical design and using electronic speed control of the compressor and fan motors. Speed control of the compressor motor was first introduced into air conditioning systems in Japan in the early 1980's. During that period, there has been a transition from induction motors to permanent magnet motors and more recently to the highly efficient interior permanent magnet motors. The continuous improvement in efficiency has also been achieved despite the requirement for input power factor correction that adds extra loss elements to the system. This paper will describe a new control architecture for air conditioning systems that optimizes the efficiency of the motor, the power inverter and the input power factor correction circuits.

II. AIR CONDITIONING SYSTEM EFFICIENCY IMPROVEMENTS

The typical home air conditioner system described in figure 1 consists of an evaporator unit inside the home, and a compressor and condenser unit outside the home [6]. The indoor fan unit draws air from the room and passes it over the evaporator heat exchanger coils where it is cooled. The compressor refrigeration cycle uses a refrigeration fluid in a closed loop system to transfer heat from the evaporator to the outside condenser unit. At the start of the cycle, high pressure liquid refrigerant passes through the expansion valve into the evaporator. The liquid refrigerant evaporates absorbing heat from the evaporator unit and so reduces its temperature. The compressor removes the gaseous refrigerant maintaining a low pressure so that evaporation continues. The process of compressing the refrigerant increases its temperature above that of the outside air. Thus the refrigerant condenses back to liquid when it passes to the outdoor heat exchanger. The liquid refrigeration exiting the condenser is then available again for the start of the cycle. The outdoor fan improves heat transfer from the condenser and helps maintain the optimum condenser temperature. When operating in steady state, the heat transfer rate per hour is determined by the heat required for the change of refrigerant phase and the volume of refrigerant circulated. Recent international protocols on the elimination of CFC greenhouse gasses have forced manufacturers to switch to less efficient refrigerants which have compounded the air conditioning efficiency problem.

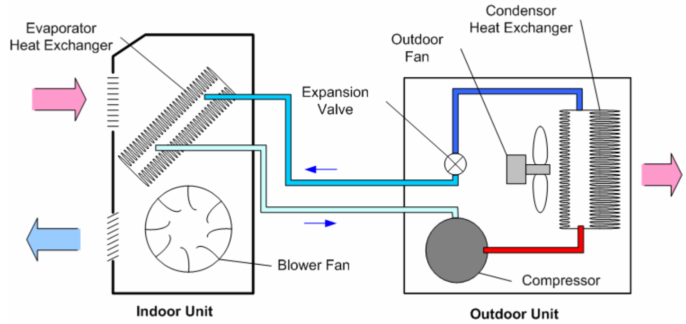

Figure 1. Home Air Conditioning System

The refrigeration cycle efficiency, measured as the ratio of heat energy, transferred to mechanical energy required for compression, and is typically in the range of 2.0 to 4.0. Refrigeration cycle efficiency improvements have been achieved through heat exchanger, compressor and fan design improvements. Optimization of the heat exchanger fins and capillary tubes improves heat transfer from the air to the refrigerant fluid. The design of rotary and scroll compressors have been optimized for air conditioning applications. Appropriate fan blade design improves efficiency and also reduces noise. However, the most significant improvement in the average air-conditioning efficiency is achieved through variable speed control of the compressor and fan motors.

In a fixed speed air conditioning system the compressor is cycled on and off to keep the temperature within a set band. For heavy load conditions the compressor operates at a high duty cycle and system efficiency is at its highest. However when the load is lighter, the compressor operates with a lower duty cycle and a much lower system efficiency. In this case a significant amount of energy is wasted after the compressor starts up before the system pressure and temperatures have built up to their optimum values. The most heavily loaded condition for the air conditioning system is after power- on since heat needs to be extracted from the room to bring the temperature within the desired level. However, the normal loading is much lighter and depends primarily on how well the room is insulated from the outside. The selection of the air-conditioner cooling capacity is a compromise between the ability to bring the room temperature within target quickly after power on and the system efficiency in normal operation. The introduction of variable speed control allows a reduction in cooling capacity in steady state to improve efficiency without compromising the peak cooling capacity and can result in system efficiency gains ranging from 15% to 40% [7]. This increase in duty cycle of the compressor operation also improves the ability of the system to remove moisture from the air and so improves the comfort level.

Control of air conditioning cooling capacity can be achieved in many ways. Mechanical methods include baffles to control the airflow across the heat exchangers. Dual compressor systems have selectable cooling capacity with one compressor only used for cooling in normal operation. However, speed control of the compressor and fan motors is the most direct method to vary cooling capacity and enables the simplest mechanical systems. Fan speed control improves efficiency by slowing the airflow across the heat exchangers and thus increasing the duty cycle of the compressor. Many US based conditioning suppliers use variable speed control of the evaporator fan alone to improve the system SEER and deliver the secondary advantage of reduced fan noise. However, using fan speed on its own shifts the refrigeration cycle operating temperature and pressures away from their optimum values. Control of the compressor speed manages the fluid flow rate in the refrigeration cycle and so matches the heat transfer rate to the load requirements. The combination of compressor and fan speed control is used by more than 90% of Japanese air conditioning manufacturers. The extra losses introduced by the speed control electronics are far outweighed by the system efficiency gains enabled by variable speed. The typical Japanese split duct home air conditioning system has one electronic control system for the outdoor compressor and fan unit and separate control units for each of the indoor fan units. The outdoor unit is often situated on a balcony so noise during operation is also a major consideration in their design. The next sections will describe the outdoor unit control system and the technology used to maximize the system efficiency and minimize the acoustic noise generated.

III. TRADITIONAL AIR CONDITIONING CONTROL ARCHITECTURE

The outdoor unit control has a typical circuit architecture shown in figure 2. There are two motor control systems one for the compressor and one for the condenser fan. In Japanese air conditioning systems permanent magnet (PM) ac motors are used for both the compressor and the fan because they are much more efficient than equivalently rated induction motors. The compressor motor is usually controlled by a microcontroller or 32 bit RISC processor that also manages the air conditioning system control functions. The condenser fan is usually supplied with the hall sensor based control circuit integrated into the housing. There is also a power factor control circuit that forces the input current to follow the input voltage wave shape and so limit the current harmonics drawn from the supply. Power factor control is now mandated by electricity regulators because the higher order current harmonics drawn by a diode bridge rectifier causes extra losses in the power network. Unfortunately, the addition of the extra inductive, power and control components required for power factor correction not only adds cost but also reduces system efficiency.

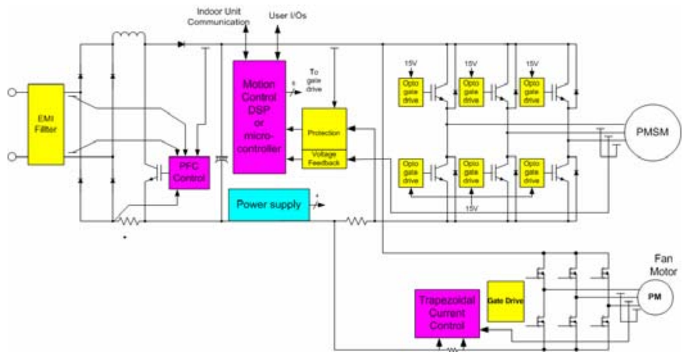

Figure 2. Traditional Air Conditioner Control Architecture

The compressor motor control schematic indicates current feedback using a shunt resistor in the dc link and voltage feedback from the compressor motor windings. The dc link current sensor is used for power inverter protection to manage the current in the motor. The winding voltage feedback is used is used for sensorless operation since the voltages applied to a permanent magnet ac motor need to be synchronized to the rotor angular position. Sensorless operation is essential because the compressor is a hermetically sealed unit and the addition of a motor position sensor and the associated wiring would be extremely difficult. This is not an in issue in the US where compressors are driven by fixed speed induction motors, but in Japan permanent magnet ac motor are used because they have almost 20% higher efficiency. The well-known back emf sensorless control algorithm can be very easily implemented using an 8 bit microcontroller or ASIC logic circuitry. The motors are selected in pairs with a six step commutation sequence resulting in trapezoidal winding currents. The commutation signals are then derived from the zero crossing of the back emf voltage in the unconnected motor winding. The fan motor controller also has a six-step commutation sequence but uses hall sensor feedback to simplify the control circuits.

Recently Japanese air conditioning manufacturers have started adopting interior permanent magnet motors due to their higher efficiency. These motors have the magnets buried in slots rather than mounted on the rotor surface. This improves robustness and reliability but the most important advantage is the 15% gain in torque per amp achieved for the same motor frame size. The extra torque is available because of the variation in the winding inductance with rotor angular position. However, to avail of this extra torque the motor must be driven with sinusoidal current waveforms rather than trapezoidal winding currents. The sensorless control algorithm now becomes more complex and requires motor phase current measurements to synchronize the applied winding voltages with rotor position. The current measurements can be derived simply using separate shunts in the inverter legs or by appropriate sampling of the current flowing in the dc link. This more complex algorithm typically requires a 32 bit RISC or high speed DSP but the next section will describe a new hardware based computation engine that very efficiently implements a sinusoidal sensorless controller for the compressor motor.

The major advantage of the six-step commutation algorithm is its simplicity and this allows the control electronics to be integrated into the fan housing. However, hall sensor alignment errors and delays in winding current commutation introduce unwanted torque spikes that produce acoustic noise. This acoustic noise problem can be solved by driving the motor with sinusoidal current waveforms but this increases the complexity of the controller. Integrated fan control solutions are available which synthesize sinusoidal winding voltage waveforms based on halls sensor feedback. These are more expensive than the six-step commuted fans but the alternative is to use a separate RISC processor or microcontroller to implement a current sensorless algorithm. Another alternative is now available since the hardware-based computation engine that implements the compressor control has the capacity to also implement current sensorless control of the fan motor. In fact the new control IC described in the next section not only combines the compressor and fan control on one IC but also integrates digital control of the input power factor correction.

IV. NEW AIR CONDITIONING CONTROL ARCHITECTURE

This section describes a new mixed signal control IC set that simplifies the control architecture for the air conditioning system outdoor unit. A single control IC integrates all the functions required for simultaneous control of the compressor motor, fan motor and the input power factor. Each motor is controlled using a sinusoidal sensorless control algorithm based on feedback from the dc link shunt. The sensorless field oriented control algorithm estimates the rotor flux position based on the applied stator voltages and the measured stator winding currents. The IC integrates the entire signal conditioning and analog to digital conversion circuits required reconstruct the motor winding currents from dc link current samples. This enables the control of both the compressor motor and fan motor with the minimal amount of external hardware.

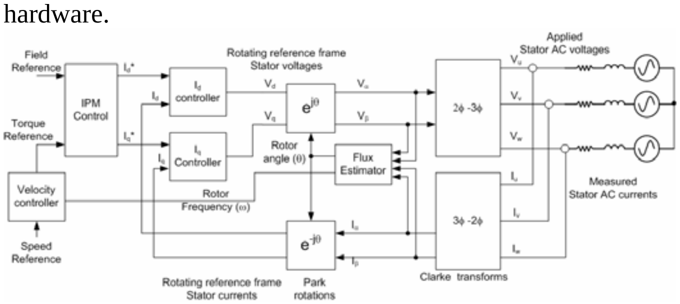

Figure 3. Field Oriented Control Algorithm

The field oriented control algorithm for the permanent magnet synchronous motor is implemented using the well known architecture shown in figure 3 [8]. The vector rotation blocks transform stator voltages and currents to the rotating reference frame making the current control loops independent of rotor frequency. The rotor angle estimation block shown estimates the rotor flux angle based stator current measurements using a model defined by the equation 1 below.

$$v_\alpha = R_S . i_\alpha + L_S . \tfrac{di_\alpha}{dt} + \tfrac{d}{dt}\left(-n.\phi_r . \cos(\theta_r)\right)$$
$$v_\beta = R_S . i_\beta + L_S . \tfrac{di_\beta}{dt} + \tfrac{d}{dt}\left(-n.\phi_r . \sin(\theta_r)\right)$$
where, (1)
$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} v_U \\ v_V \\ v_W \end{bmatrix}$$

This control architecture also includes an additional block to calculate the phase angle advance required to maximize torque when driving an interior permanent magnet (IPM) motor. The IPM motor is inherently more efficient than a surface magnet motor because of the extra torque that can be produced due to the magnetic saliency. The torque equation for an interior permanent magnet machine includes the usual term that is a function of the stator current and rotor flux and an additional term that is a function of the a square of the stator current and the saliency of the rotor. The combined torque angle function in figure 4 shows that to maximize torque the current phase angle should be advanced at higher torques. The final outer loop is the velocity loop that takes its speed input from the angle estimator.

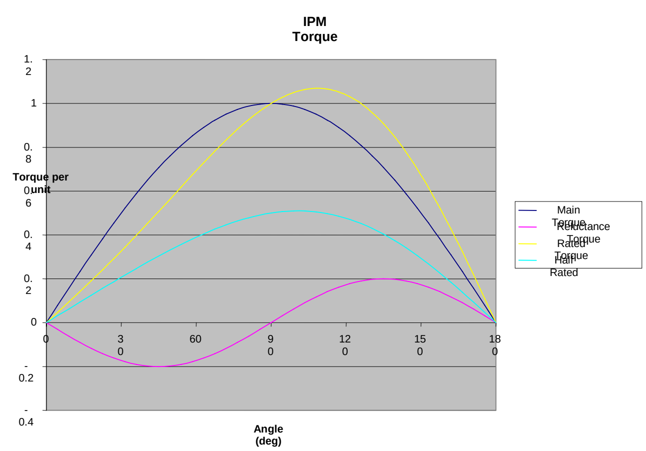

Figure 4. Reluctance Torque versus Angle

The current and velocity control algorithms are implemented in hardware using an embedded Motion Control Engine™ without requiring any software development. The Motion Control Engine (MCE), illustrated in figure 5, contains a library of control elements such as Park and Clarke transformations, PI control, limit, and summation functions that are required ac motor control. Each of these functions is implemented using customized ASIC hardware that optimizes execution speed and minimizes silicon area. A schematic entry tool is used to define the control architecture graphically by interconnecting blocks imported from the MCE library. A number of the library elements such as the vector rotation blocks can be called multiple times but obviously hardware interface blocks, such as the PWM controllers can be only used once in the schematic. A graphical compiler directly translates the control schematic net list into a set of instructions for the motion control sequencer within the MCE hardware. This approach combines the execution speed advantage available from ASIC implementations but still has the flexibility of a programmable system. However, the control engineer can completely bypass the multiple steps required to translate the control algorithm into a set of stage equations that are coded in software. The Motion Control Engine significantly speeds up the design time and minimizes errors by eliminating software from the control algorithm development cycle.

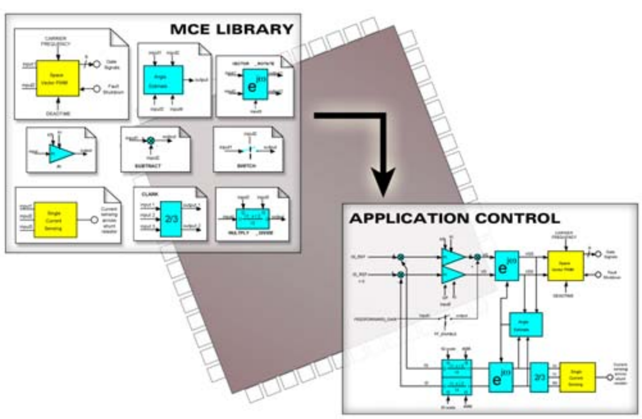

Figure 5. Motion Control Engine

The input power factor is also controlled using the mixed signal air conditioner control IC. The input converter, shown in figure 6, uses a bridgeless topology that reduces the number of power device voltage drops to two compared to three voltage drops using the conventional boost topology. The signal conditioning and sampling circuits for power factor correction are also integrated into the mixed signal IC so that the only external components required are passive. The digital power factor correction algorithm is also implemented on the Motion Control Engine using control blocks typically used only for ac motor control. The first prototype digital control scheme was a simple digital implementation of the standard analog implementation with a digital current loop and a current reference derived from the rectified ac voltage. The performance of this prototype did not meet the requirements as expected since the bandwidth of the digital current control loop was an order of magnitude lower than that typically analog implementation.

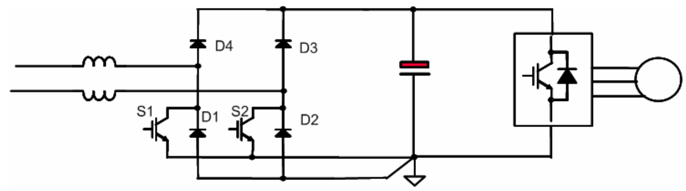

Figure 6. Bridgeless power factor converter topology.

The current loop bandwidth needs to be greater than 10 kHz to follow the reference waveform because of the many higher orders harmonics. It is not practical to implement such a high bandwidth current controller using the Motion Control Engine because this would use up most of the computation capacity and leave very little left for the motor control algorithms. The improved algorithm uses a feed forward technique to lower the current loop bandwidth required to meet the harmonic standards. This feed forward algorithm makes use of vector rotation blocks normally used in the ac motor field oriented control loop. A significant performance advantage gained is a lowering of the switching frequency and a reduction the input inductance that minimizes losses. The waveforms in figure 7 demonstrate the improvement in current waveform using this new approach.

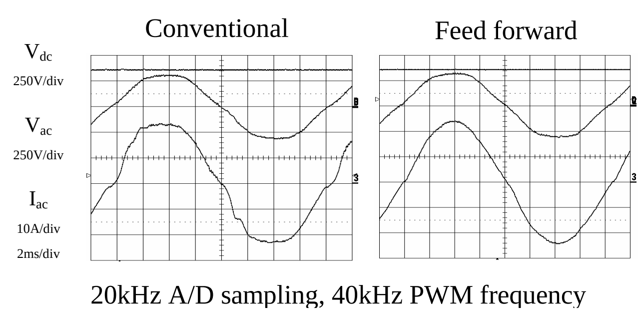

Figure 7. Current Waveform improvement using voltage feed forward.

V. SYSTEM PERFORMANCE

The complete air conditioning design platform includes the digital control IC and a set of integrated power modules for the compressor, fan and input power stages. The control schematic in figure 8 demonstrates the significant simplification from the traditional air conditioning control architecture. The power modules integrate the high voltage gate drive circuit, the power switches and the dc link shunt in a ‘single in line’ package. This provides a more efficient thermal design and simplifies assembly resulting in greater reliability. The gate drive circuits not only provide the isolation between the power and control circuits but provide protection functions such as under voltage lockout and over current protection.

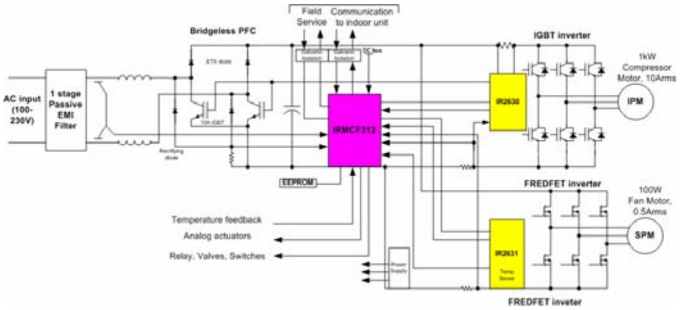

Figure 8. New Air conditioning control architecture

The digital control IC internal structure is described in figure 9 below. The IC includes the Motion Control Engine that implements the sensorless control algorithms for the two motors and also a co-integrated application microcontroller to implement system functions such as the speed temperature profile or valve control. An important feature is that this 8 bit processor that can operate completely independently from the Motion Control Engine using dual port memory as the communication interface. This offers significant advantages over traditional RISC or DSP based controllers that require the slow systems application to share resources with the high speed control applications. The application processor can access all the control system variables that are stored in the dual port memory and can perform diagnostic functions without interrupting the operation the motor control algorithm execution.

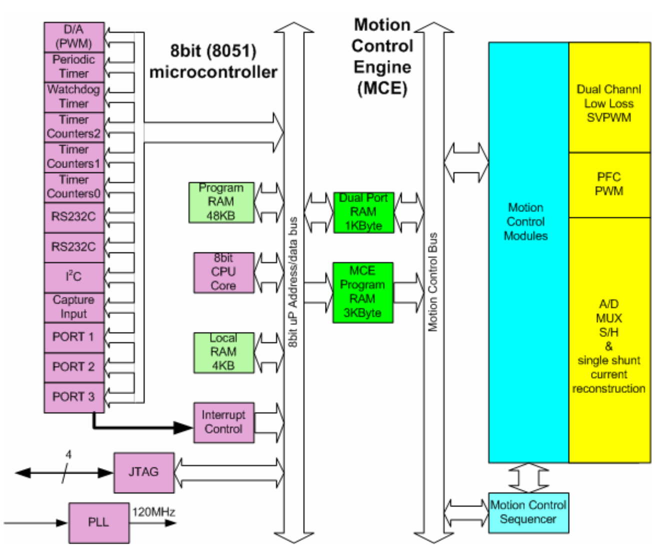

Figure 9. Control IC Internal Architecture

The efficiency of the compressor inverter and the input power stages have been improved using new depletion stop trench IGBT's that offer both a low on state voltage and low switching loss. This combination of the highly efficient power switches, the optimized torque control of the IPM motor and a low loss power factor correction algorithm yields a significant efficiency improvement. The curve shown in figure 10 below is a plot of the combined PFC and compressor inverter efficiency over the operating input power range. A maximum efficiency of over 95% is achieved with an input converter switching frequency of 40 kHz and a compressor running at 5200 RPM with an inverter switching frequency of 6 kHz. This efficiency is a number of percentage points higher than typically available in the market. The efficiency gain was achieved while still meeting the input current harmonic standards.

VI. Conclusion

This paper has described some of the improvements in air conditioning system efficiency over the past number of years. It has outlined the economic and environmental benefits to society that can result from this continuous improvement in efficiency. A new air conditioner system architecture is introduced that demonstrates significant performance improvements over previous generation systems making it a powerful tool in the next phase of efficiency improvement. An important feature of this new architecture is the simplicity in mechanical and electronic design that eases its widespread adoption. This will become increasingly important as energy resources become scarcer in the future.

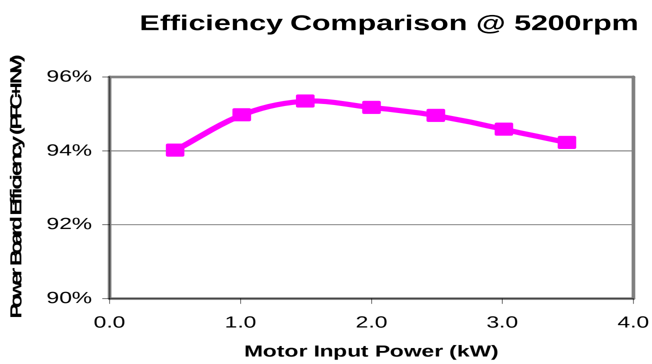

Figure 10. Air conditioning system performances.

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