International Rectifier

New iMOTION™ appliance-motor control mitigates growing energy crisis in China

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Abstract— Estimates are that more than half of all electricity in China powers motors. The traditional mechanical control scheme wastes half of the electricity it uses. Inverter-based, variable-speed-drive designs can save most of these losses.

Advancing the adoption of inverter-based variable speed drives requires finding a means to achieve mechanical simplicity while maintaining the performance necessary to meet high-efficiency goals. A new *iMOTION™* chipset consists of a unique MCE (Motion Control Engine) and a dedicated high-voltage IC to drive a PM (permanent-magnet) motor. This paper presents the chipset in the context of an air-conditioner design with corresponding test data.

Keywords: hardware computation engine, MCE, FOC, sensorless sinusoidal control, IPM, SPM, IM

I. INTRODUCTION

China is facing a significant imbalance of energy supply and demand. Supply resources cannot catch up with the growth of energy demand that has accompanied the country's rapid expansion of industrial activity and growing adoption of automobiles and household appliances. Key to solving this energy-imbalance problem is to introduce more energy-efficient products across both industrial and residential segments. A variable-speed motor control can serve as a key conservator of electrical energy. However, during the past decade, market forces have hindered the expansion of inverter-based motor drive systems, particularly in home-appliance applications. Among these are the fact that the China market requires a relatively lower purchase price for home appliances than do markets in other developed regions such as Japan and Europe. The capability of local appliance manufacturers to adopt a new inverter technology also took more time then expected. Recent improvements in the ability of local manufacturers to develop more energy-efficient products by incorporating the latest inverter technology, in concert with the establishment of Chinese government guidelines for energy efficiency, have accelerated the adoption of inverter-driven products.

The economic impact resulting from a manufacturer's choice of motor type has also drastically changed. Until now, industrial applications and home appliances primarily used the IM (induction motor). Increasing steel prices and decreasing prices of magnetic materials—trends that many industry watchers expect to continue—have made PM (permanent-magnet) motors more economic. The PM-motor adoption rate, therefore, should accelerate in the coming decade, particularly in low-power applications such as domestic air conditioners and washers.

The challenge is to employ advanced PM motors in a price- and performance-competitive, inverter-based, home-appliance control system to achieve simultaneously cost reductions through mechanical simplification and high-energy efficiency. Success in facing this challenge will require that both appliance designers and their power-electronics component suppliers take a more in-depth view of the system design. International Rectifier's iMOTION™ Integrated Design Platform combines the motor-control-subsystem architecture, chipset, and control algorithms to satisfy the two goals stated above. The chipset achieves high efficiency by employing an IPM (interior permanent-magnet) motor, which offers higher efficiency than either an IM, or SPM (surface permanent-magnet) motor for air-conditioner applications. It consists of a new controller based on a proprietary Motion Control Engine (MCE) and a new high-voltage analog IC, which solves unique air-conditioner-application problems. This paper begins with the current status of energy-saving issues and presents an in-depth discussion of an air-conditioner outdoor-unit design. It includes analyses of the advantages that the iMOTION™-based approach offers and presents test results.

II. GROWING ENERGY DEMAND AND NEW ENERGY GUIDELINE IN CHINA

The China industrial segment has grown significantly during the last decade. Domestic steel consumption, for example, has increased by more than a factor of two since 1994. Since 2001, China's consumption of steel has grown by 30 million tons annually to reach 335 million tons in 2005, keeping China in the number-one position in the world, surpassing the combined steel consumption of the United States and Japan. The International Steel and Iron Association predicted that in 2005, China would consume 31% of the world's total steel production.

The growth in China's steel consumption is not only due to factory and new-building construction, but also follows the significant growth of electric equipment in industry, commercial, and residential areas—trends that have contributed to the rapid increase in energy demand.[1]

Figure 1 shows historical and projected China energy supply-and-demand data. The forecast indicates that, should current trends continue, China will face a serious energy shortage within a few years.[1] Already familiar periodic electric supply "blackouts" are common in the booming southern and eastern regions of the country. Estimates suggest that China will exceed 2.4 trillion kWh this year, 277 billion kWh more than last year.

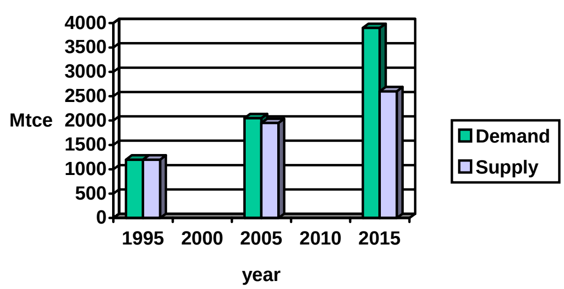

Figure 1: Energy Supply and Demand in China

China has considered ways of improving energy efficiency in recent years. One initiative establishes energy efficiency guidelines similar to European standards that incorporate Class categories for home-appliance products. China introduced the EER (Energy Efficiency Ratio) in 2005 for home appliances and, starting in March of that year, mandated the energy label shown in Figure 2 for all new home-appliances.

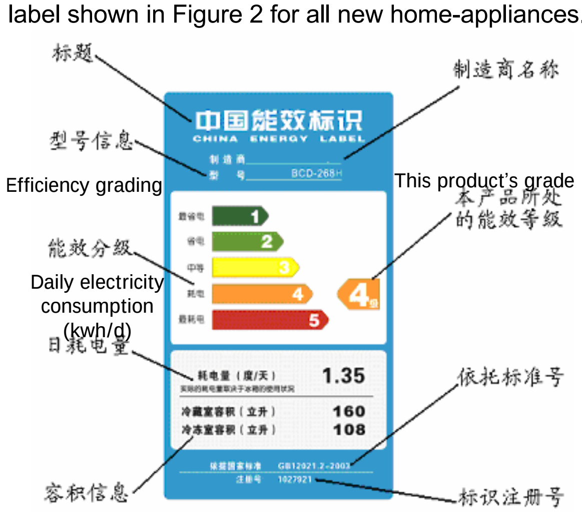

Figure 2: Energy Efficiency Label in China

China(CC≤4500)		European
Grade	EER	Grade
1	3.4	
2	3.2	A
3	3.0	B
4	2.8	C
5	2.6	D

Table 1: EER requirement in China

Table 1 shows the EER requirements for air conditioners. Current requirements do not allow the sale of units with EERs less than 2.6.

III. IMPACT OF INVERTER-BASED APPLIANCE ELECTRONICS IN CHINA

In 2000, China produced 14M air conditioners and 14M washers. Today China produces 48M air conditioners and 23M washers. This exceeds the volumes used in Japan and Korea. Among residential appliances, air conditioners currently enjoy the fastest growth rate.

The CoP (Coefficient of Performance), given by equation (1), indicates an air conditioner's efficiency.

CoP = heating or cooling power ÷ input power (1)

For example, in Japan the CoP exceeds five for leading 2.2-kW-cooling-power air-conditioner systems. In other words, 400W of AC input power develops 2.2 kW of cooling power. In China, a typical CoP for a 2 kW air conditioner is around 1.3 (Figures 3 and 4).

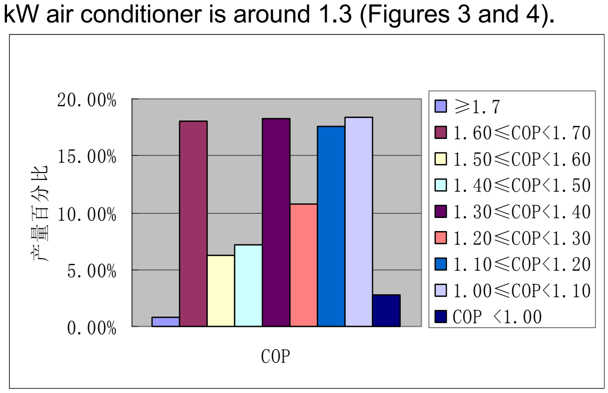

Figure 3 China air conditioner COP

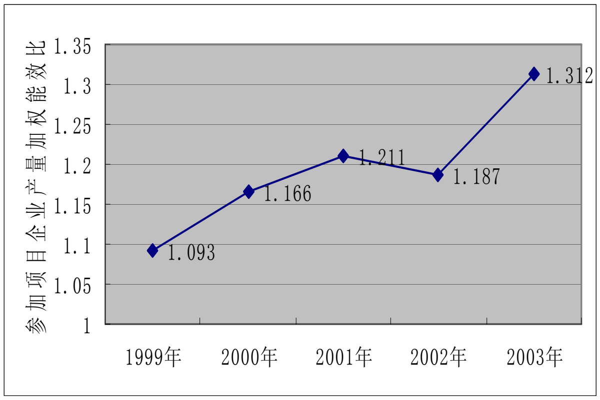

Figure 4: China air conditioner COP history

This low CoP results from the fact that most air conditioners use IM compressors with on/off controls. When a PWM inverter drives the IM the CoP increases to 3.5. A PM motor compressor delivers the greatest efficiency, particularly an IPM, which yields a CoP near 5.5.

Based on this observation, we can calculate the effective energy savings for each 2 kW household air-conditioner system. Assuming a four-month usage period between June and September, the typical household savings is 0.97 kW for an IM-based air conditioner and 1.18 kW for a PM-based unit when compared to a device with on/off controls. If all 48M air-conditioner units were inverter-driven, then a 55.3B kWh annual savings would result. Savings per household correspond to 622 RMB/yr with IM-based air conditioners, increasing to 757 RMB/yr when PM units replace air conditioners with on/off controls.

IV. MOTOR FOR APPLIANCE ELECTRONICS WITH VARIABLE SPEED APPLICATION

Globally, IM and PM motors dominate appliance applications. Such applications in China have historically depended on IMs. However, recent steel-price increases have made PM motors more attractive because IMs use more steel PM machines. Due to its greater losses, an IM requires a greater volume to deliver the same power compared to a PM motor. But higher magnet-material costs have prohibited the use of PM motors for low-cost home-appliance applications.

Table 2 shows a cost comparison for 750W appliance motors for washer applications. The magnet cost is less than the savings in steel costs resulting in a lower total cost for a PM motor.

In terms of torque per amp and loss, a PM motor has distinct advantages over an IM. An IM draws current in a rotor cage structure to produce torque.

	IPM motor		Three-Phase Induction Motor	
	Weight	Cost	Weight	Cost
Magnetic Steel (Before Stamping)	3595g □107×40L	$2.86	4760g □105×55L	$3.79
Copper Wire	367g	$1.81	500g	$2.46
Aluminum	550g	$1.41	600g	$1.54
Magnet	316g	$0.69	-----	-----
Total		$6.76		$7.79

Table 2: 750W motor cost comparison

The associated secondary circuit loss does not exist in a PM motor. An IPM motor provides greater torque per amp than a PM motor, especially an IPM motor in conjunction with reluctance torque control, which provides the greatest efficiency of any motor type. The second term in Equation (2) is a reluctance torque. The main torque reaches its maximum at β=0º; the reluctance torque at β=45º. Figure 5 illustrates these two torque components, the combination of which yields a torque maximum between β=0º and β=45º depending on the quantity {Lq – Ld}. The bigger the difference between Ld and Lq, the larger is the resulting torque.

$$T = P_n\{\Phi_0 I_q + (L_q - L_d) I_q I_d\}$$

$$or \qquad (2)$$

$$T = P_n\left\{\Phi_a I_a \cos(\beta) + \frac{1}{2}(L_q - L_d) I_a^2 \sin(2\beta)\right\}$$

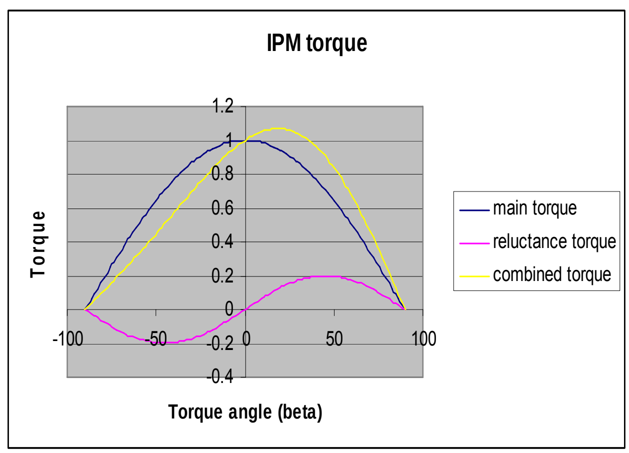

Figure 5: IPM reluctance Torque and its angle

Figure 6 shows a loss analysis among various types of 750W motor, where IM = induction motor, SyncRM = synchronous reluctance motor, SPM = surface-magnet PM motor, IPM = Interior permanent-magnet motor. An IPM generates less than half the loss of an IM.

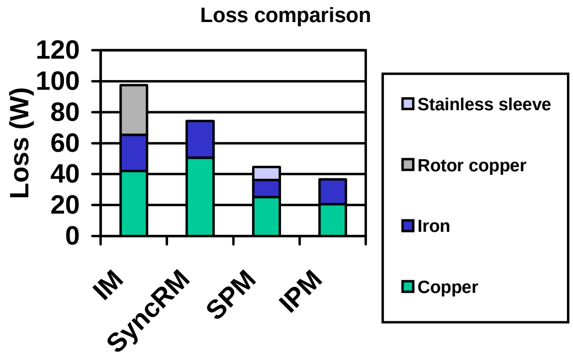

Figure 6: Loss Comparison of various motors

V. HIGH ENERGY EFFICIENCY SOLUTION FOR AIR CONDITIONER OUTDOOR UNIT

Traditional inverter-based air-conditioner units merged in two ways in recent years. One is imported from Japan mainly through existing Japanese manufacturers as a finished good. The other is developed and manufactured by local manufacturers. Japanese imported air conditioner units typically employ either a scroll type or twin rotary type compressor. This is mainly due to the unique requirement in Japan that low-vibration and quiet operation overweigh the cost. These compressors cost greater than 40% more than a single rotary compressor which prone to larger vibration and acoustic noise. The inverter control architecture employs an advanced 32-bit RISC microcontroller to control a compressor in addition to a separate fan inverter and PFC (Figure 7).

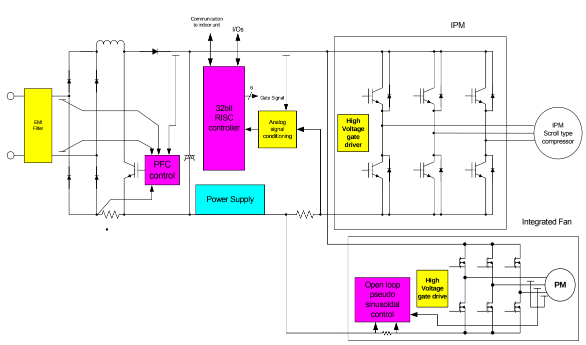

Figure 7: Traditional Japanese outdoor unit

In China, after a decade of import history, this design has not penetrated well due to its high cost structure, which stemmed from its expensive compressor and complex inverter control. The latter approach evolved using an IM compressor with an open-loop V/Hz control, an on/off fan control, and a separate PFC (Figure 8). Although this design's cost is similar, the improvement in energy efficiency was insufficient to provide sufficient electric-bill savings and, therefore, penetration was limited as well.

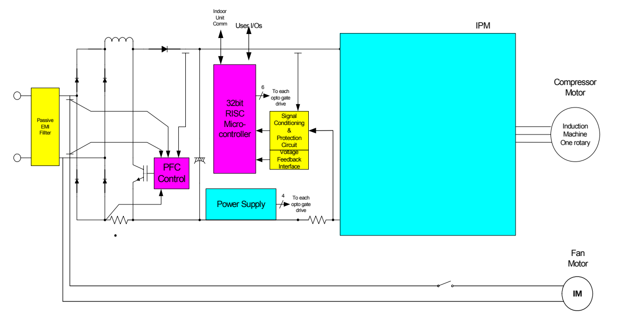

Figure 8: Traditional IM-based outdoor unit

International Rectifier has recently introduced the iMOTION™ integrated design platform to solve this efficiency challenge. The iMOTION™ chipset allows the use of a single rotary compressor while maintaining quiet, low-vibration operation. Application-specific versions of the chipset include the IRMCF312 air-conditioner controller and a new high-voltage analog IC.

1. New MCE controller – IRMCF312

The IRMCF312 is a new air-conditioner controller based on a new MCE (Motion Control Engine) architecture—a unique hardware control engine that provides a fast-computation algorithm for digital PFC control and sensorless sinusoidal position control for an IPM and a fan. With this IRMCF312, a designer can eliminate the separate fan controller and separate analog PFC control function. The chip only requires a DC link current-sense shunt resistor for sensorless FOC (Field Oriented Control) by incorporating a dedicated fast analog circuit along with a 12bit A/D converter for reconstructing the motor phase current. The controller, therefore, requires no external active components and it provides a direct interface to each shunt resistor. To achieve high PFC performance, the IRMCF312 integrates dedicated operational amplifiers which allow a direct interface to the AC line voltage and the DC bus voltage via external resistors. In typical circuit configuration, when compared to the leading manufacturers' 32-bit RISC microcontroller, the IRMCF312 eliminates five external operational amplifiers and their associated sample/hold circuit. The IRMCF312 performs the computations for a complete sensorless sinusoidal FOC in 12µs with a 64MHz internal clock selection. The IRMCF312 also contains an 8-bit microcontroller to facilitate computation and control for non-drive tasks such as sequencing and communication with UART, I^2C/SPI, timer/counter, capture, and digital I/O peripherals. Figure 9 shows the internal block diagram. The MCE requires no coding effort unlike traditional DSP- or microcontroller-based controllers. Programming is done by graphical control block editing through a Matlab/Simulink tool (Figure 10).

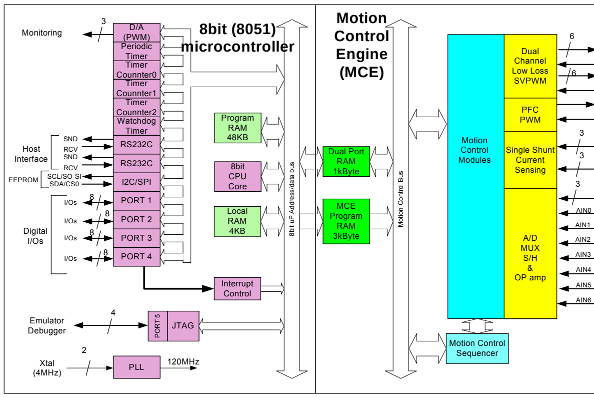

Figure 9: IRMCF312 block diagram

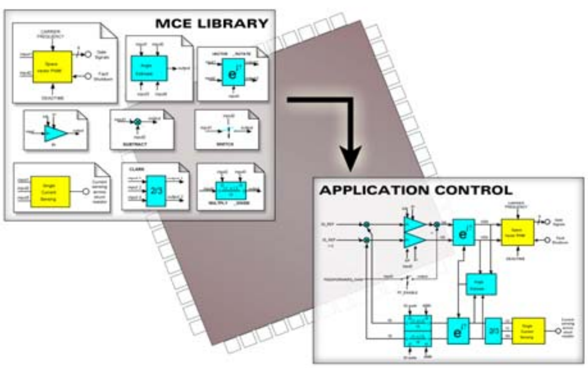

Figure 10: The MCE (Motion Control Engine)

2. Air-conditioner-specific high-voltage IC

The new high-voltage IC is a companion device to support a cost-effective, efficient, outdoor air-conditioner design. This high-voltage IC includes an additional PFC driver and ground-fault-detection circuit in addition to the inverter IGBT-gate drive and over-current protection functions. The ground-fault-detection circuit enables the direct interface to high-side series shunt resistors without additional circuitry or power supply. The IC also contains diagnostic interrogation logic to facilitate fault identification without extra pins. International Rectifier has also developed a new intelligent power module containing this IC together with the latest trench gate IGBTs.

Figure 11 shows the complete iMOTION™ outdoor air-conditioner design. The chipset simplifies the design by eliminating more than 10 active components including a PFC controller and a Hall-effect current sensor for high side ground fault detection. Comparing this design to the traditional approach, the iMOTION™ chipset enables a highly efficient air-conditioner a low cost single rotary compressor and few external components.

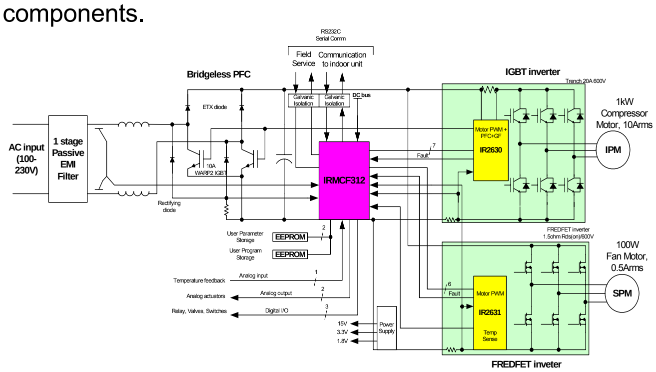

Figure 11: iMOTION™ based outdoor unit design

3. Test Results

Figure 12 shows a scope picture illustrating compressor motor current, fan motor current, PFC current, and input AC voltage waveform under full-load conditions. The PFC and compressor current waveform scales are 10A per division; the fan current waveform scale is 1A per division. The PFC control is based on a bridgeless configuration (Figure 9), which the MCE digital PFC algorithm controls. The compressor and fan PWM frequency are 6kHz and 18kHz respectively. The 380V DC bus derives from the 220V AC input. All three control functions run in parallel for a 4kW air-conditioner application. The compressor uses a 4-pole IPM motor with an Ld/Lq ratio of 3.5 running at 5200rpm. The fan is an SPM motor running at 1000rpm. The IRMCF312 controls both motors without position sensors and requires only shunt resistors in the DC link.

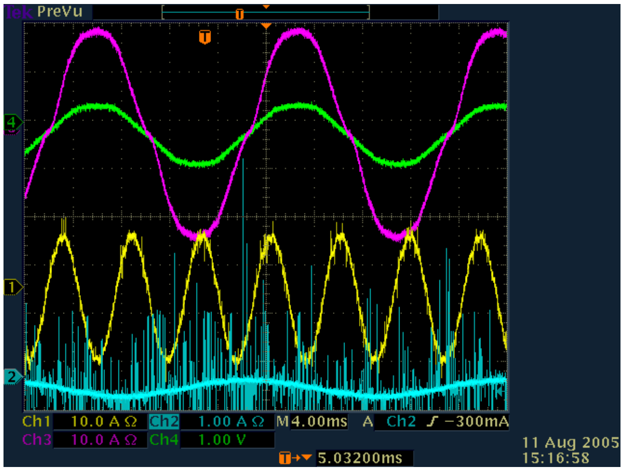

Figure 12: PFC, compressor, fan current

Figure 13 shows inverter-plus-PFC efficiency data based on AC-input and inverter-output power measurements. The PFC operates in continuous-current mode with a 20kHz digital-computation update rate and a 40kHz PWM carrier frequency. The combined efficiency of the PFC and inverter exceeds 95%—a 5% improvement over the most efficient air conditioners currently available in the market.

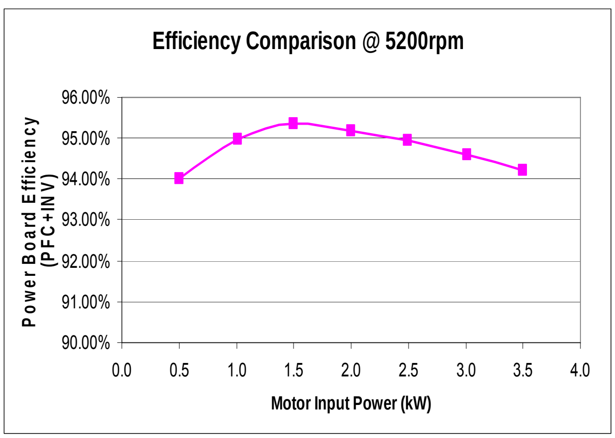

Figure 13: Efficiency test result (PFC+compressor inverter)

VI. CONCLUSION

Serious energy supply-and-demand issues in China have been discussed. It has been shown that energy-efficient appliance electronics play a significant role in easing the energy-demand crisis and provides an economic benefit for each household. A new iMOTION™ chipset has been discussed that improves efficiency and reduces cost. The paper showed that the chipset simplifies integration while yielding high efficiency for future air conditioner designs.

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