TOSHIBA

Complete control of a heat pump outdoor unit using a single MCU

Introduction

The heat pump has become a key appliance in the attempts to achieve net-zero carbon emissions by the middle of the century. A heat pump offers a method of heating domestic and office spaces with less energy than conventional designs based on electric resistive heating and with lower carbon dioxide emissions than oil or gas-fired heating.

The key to the lower overall energy consumption of the heat pump compared to joule heating lies in its role as a heat exchanger. Instead of generating heat purely from driving current through a resistive element, a heat pump extracts heat from external sources and transfers it to the area that needs it. The process can be reversed so that in summer, a heat pump can provide cooling instead by removing heat from indoors and releasing it into the external environment. The result is a system that can provide consistent and even heating and cooling throughout a building year-round.

Today’s heat pumps cost more than traditional heating and air-conditioning systems, though lower running costs should pay back that investment. But, to meet net-zero targets and allow a wider range of users to take advantage of the technology, there is pressure to reduce manufacturing costs wherever possible. This pressure extends down to the electronics used to control the heat pump, particularly as the control algorithms are more complex than those found in conventional space heaters.

Types of heat pumps

The most common form being installed at this point is the air-source heat pump. It can be used in a wide variety of situations. Air-source heat pumps are suitable for residential, commercial, and industrial buildings. They are best suited to moderate climates but can also operate efficiently in colder climates. Their major advantage in terms of installation flexibility is that they do not need significant amounts of external pipework.

Ground-source heat pumps take advantage of the relatively stable temperature of soil or groundwater below the surface. This helps maintain round-year efficiency, providing consistent heating and cooling. They are suited to larger domestic properties and commercial buildings as they need a significant amount of area around the building to accommodate loops of buried pipework that are used to transfer heat to and from the ground.

Water-source heat pumps extract heat from a water source such as a lake, river, or well or use the water body as a heat sink. These heat pumps are most often used in larger commercial buildings and domestic apartment complexes.

A further option is the hybrid heat pump. This type of system combines the heat-exchanger components with some form of additional heating element, such as electrical resistance heating. Hybrid heat pumps offer flexibility and efficiency by switching between energy sources based on factors such as the outdoor temperature differential.

Heat pump architecture

An air-to-air or air-to-water heat pump installation is normally divided into two modules. One module is placed outdoors and is typically larger as it contains the refrigerant tank, compressor, fan, and evaporator/condenser unit. This is paired with a smaller indoor unit that contains motors to direct the flow of fluid through the heating system in addition to a second evaporator/condenser unit and the user interface panel. The two units cooperate to exchange heat between the two modules using a refrigeration-type process that directs gases between the two modules in paired compression-condensation and expansion-evaporation cycles.

During heating or cooling cycles a refrigerant gas is pumped between the two modules. When compressed, the gas increases in temperature due to the increased pressure. Heat is transferred from the compressed gas to air or water that is passed across the surface of the heat exchanger before being circulated around the building. When expanded, the gas cools, which can be used for cooling. In this way, heat can either be drawn from the outside to the house or moved from the house for cooling. For air-type heat pumps, a fan helps increase the output of the heat exchanger.

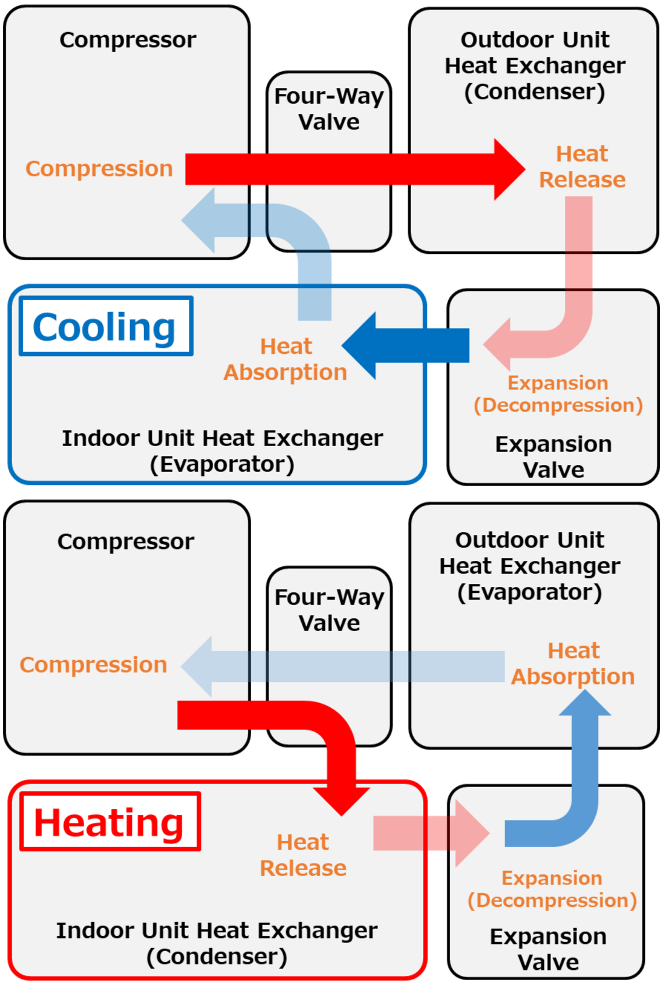


Figure 1 – Flow of refrigerant through a heat pump

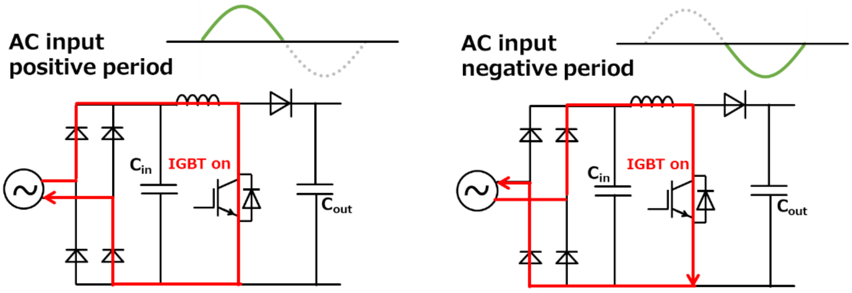
This process of exchanging heat is key to the heat pump's apparent high efficiency. In principle, under the right conditions, the coefficient of performance (COP) can be more than 7. The pump can deliver more than 7kW of heat using just 1kW of electrical power. Practical considerations and temperature variations over the year lead to a lower coefficient of performance or seasonal energy efficiency ratio. It is common to achieve figures ranging from 2.5 to 5. By comparison, a conventional water boiler will deliver only about 90% of the delivered power into useful heat, resulting in a coefficient of performance that is less than 1.

Temperature differentials affect heat pump efficiency. The wider the difference in external and internal temperatures, the lower the coefficient of performance. This has helped drive the development of different types of heat pumps such as ground-source designs, because they are less affected by seasonal differences in air temperature.

Motors and power conversion in heat pumps

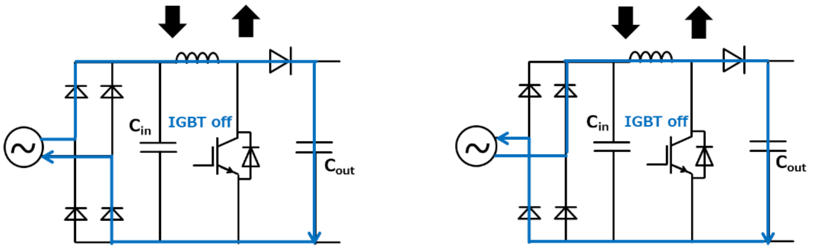
Power-conversion control for rectifiers and inverters is key to improving the overall efficiency of heat pumps. Advanced power-conversion algorithms coupled with carefully chosen power components minimise losses that would otherwise compromise energy efficiency.

There are several key power-conversion stages inside the typical heat pump. This starts with the AC input stage. The rectifier takes in AC wall power and converts it to DC for distribution to the different motor inverters and control electronics. This rectifier will need to employ power factor correction (PFC) to prevent the generation of high levels of reactive power that would result from just using a classic diode-bridge circuit. Though the deviation from the ideal power factor can be smoothed using a capacitor, the resulting ripple deviations will generally inject harmonics into the AC supply waveform that contravene local design regulations.



(a) Current path when IGBT is on

(c) Current path when IGBT is on



(b) Current path when IGBT is off

(d) Current path when IGBT is off

Figure 2a – General operation of a PFC circuit

Active PFC circuits deliver a better level of phase correction. An active PFC circuit typically uses a boost-chopper configuration to control the flow of energy using multiple switching operations. During each switching cycle, energy is transferred from the grid supply to the output. By controlling the duty cycle of these switching operations, the circuit shapes the current waveform to follow the sine-wave profile of the input voltage, delivering a power factor close to unity.

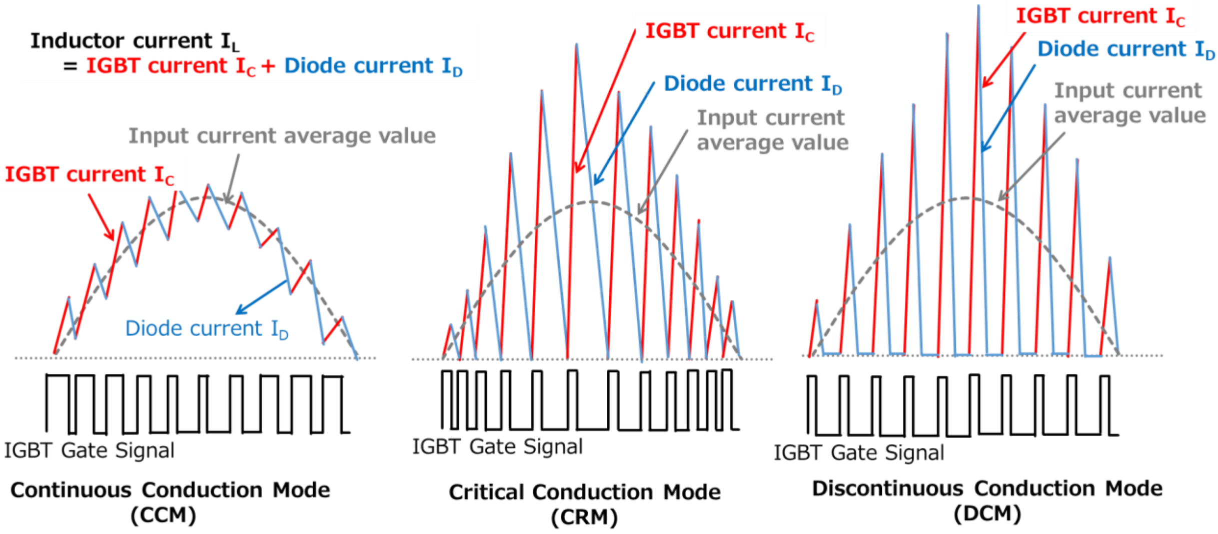


Figure 2b – a ripple in a rectifier circuit with different PFC modes.

Control of the duty cycle typically uses one of three modes: continuous conduction mode (CCM); critical conduction mode (CRM); or discontinuous conduction mode (DCM). CCM is designed to pass current continuously. This helps deliver a smaller current ripple than other PFC techniques though it results in a reverse-recovery current being superimposed on the PFC inductor current when each power transistor is switched off and so favours the use of devices with fast recovery times. The other two techniques switch the power transistor on only when the current through the inductor has fallen to zero, which increases the output ripple. CRM switches the power transistor on once the current has fallen to zero. DCM adds a delay period to avoid reverse-recovery losses but suffers lower efficiency than the other two modes.

Several motors are core parts to the heat pump's main functions. Central to the architecture is the motor used in the compressor. There will also be a motor used to drive the fan on the outdoor unit and further motors may be used. Circulating pumps and valves, based on either motors or solenoids, help control the flow of refrigerant gas or liquid through the indoor heating system. Low-power PMSM/BLDC motors may be used to drive further fans for indoor air distribution.

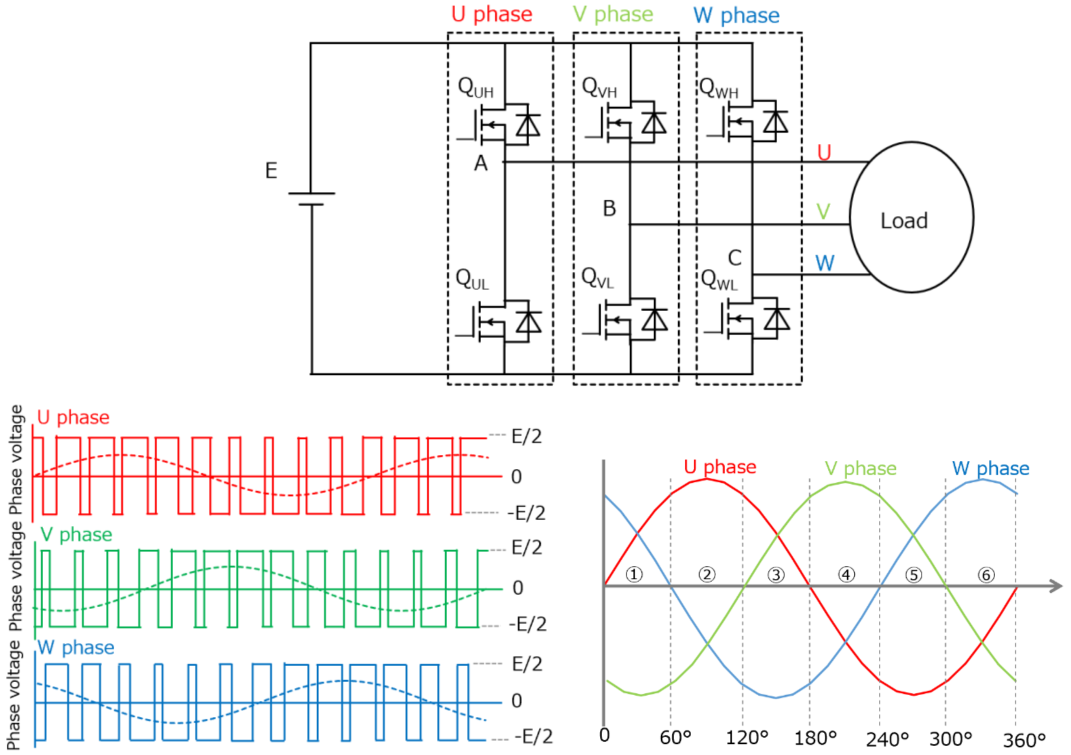
These motors can use a comparatively simple control scheme. One such method is trapezoidal control. Using this method, three position sensors feed the current rotor position back to the controller. The state of the rotor sensor is used to feed current to two of the windings while leaving the third open circuit. This generates a consistent rotational force suited to fans that do not change their speed often. This results in a trapezoidal back-EMF signal, which gives the scheme its name. But it generates a torque ripple caused by the insertion of dead-time intervals. These intervals are needed to prevent the shoot-through of current when complementary transistors in an inverter switch on and off.

However, with such a simple method, the resulting torque ripple leads to the motor generating unwanted noise and vibration, which is problematic in domestic environments where people may sleep close to the heat pump’s external unit. Although one way to deal with this issue is to adopt sinusoidal commutation, this requires more accurate and expensive position encoders and the use of lookup tables to provide accurate output waveforms. The benefits also reduce at high speed.

The most complex control requirements are for the motor used in the compressor. This motor will encounter the greatest variability in operating conditions and torque requirements due to the large changes in gas pressure in the chamber. Also, this is the largest power consumer of a heat pump and therefore critical for efficiency.

The inverter operates across three phases to deliver power to each of the stator windings that control the motion of the rotor. To determine the amount of power required by the motor, drives traditionally employed scalar control techniques, such as volts-per-hertz. This is a simple control strategy that attempts to maintain a constant flux level to avoid saturation. Using this control strategy, the voltage and the rate at which motor windings are powered by an inverter are varied to control the motor's speed. The drawback of this method is that it does not consider the motor's torque requirements, which will change under different load conditions, such as when the compressor is at the extremes of high or low pressure. Some other methods such as direct torque control attempt to consider the change in torque conditions but tend to suffer from high torque ripple, which can lead to unwanted losses.

By accurately modelling the motor's magnetic field and using that mathematical model to predict the motor’s state, field-oriented control (FOC) minimises losses overall and improves efficiency. FOC enables precise control of motor speed and torque, allowing for rapid adjustments to changing load conditions. This responsiveness ensures that the motor operates at its optimal efficiency under varying load and speed requirements, reducing energy waste during transient periods.



(a) Output phase voltage waveform of each phase

(b) Average output phase voltage waveform of each phase

Figure 1: Three-phase inverter and waveforms

FOC helps to reduce harmonic distortion in the electrical system by controlling the current waveform applied to the motor to a sinusoidal shape. This results in smoother operation and reduced losses associated with harmonic currents, contributing to overall energy savings. When the motor operates more efficiently, it generates less heat, which reduces the need for cooling systems and improves overall system efficiency.

One key advantage of FOC is that it can also be driven without sensors to detect the motor's rotor angle: the algorithm can determine motor state and position by measuring the current flowing through the motor. A simple shunt resistor can measure this current. However, without dedicated hardware support in an MCU, sensorless FOC can be challenging to implement: it relies on complex arithmetic performed at speeds beyond the capabilities of simple microcontrollers used in motor drives.

By taking advantage of hardware support for FOC in MCU devices designed for these applications, the heat pump designer can benefit from more efficient and quieter operation and remove the need to use costly position sensors or encoders.

Integration

As a sensorless, sinusoidal variable-frequency commutation method, FOC needs to derive at high frequency several key parameters from changes in current flow from the signal provided by a shunt circuit. Once calculated, further transformations are required in real-time to support algorithms that operate in a rotational frame of reference. This extensive sequence of operations calls for repeated multiplications together with sine and cosine trigonometric functions that are used to transform between coordinate frames.

A processing solution for FOC control needs to include appropriately dimensioned analogue-digital converters, a processor that can handle vector mathematics for the transformations and the flux-estimate algorithms. This poses two problems for traditional MCUs. They rarely have the appropriate instructions. To make use of these devices, developers need to use software functions based on lookup tables for the trigonometric functions together with multi-instruction emulation of complex multiplications. Conversely, a digital signal processor (DSP) that has required hardware support for these operations will generally lack the infrastructure needed for interrupt-driven input/output control. As a result, designers employing these devices in a heat pump would need to use a combination of processors and other devices to manage each of the power-control domains.

MCUs such as the TMPM4KL from Toshiba take care of this problem by integrating the company's highly optimised and FOC specialised Advanced Vector Engine (A-VE). This accelerator module implements the additional functions needed for efficient FOC. The TMPM4KL combines acceleration for FOC with hardware units dedicated to pulse-width modulation (PWM), which mediates the flow of power to each of the inverter phases.

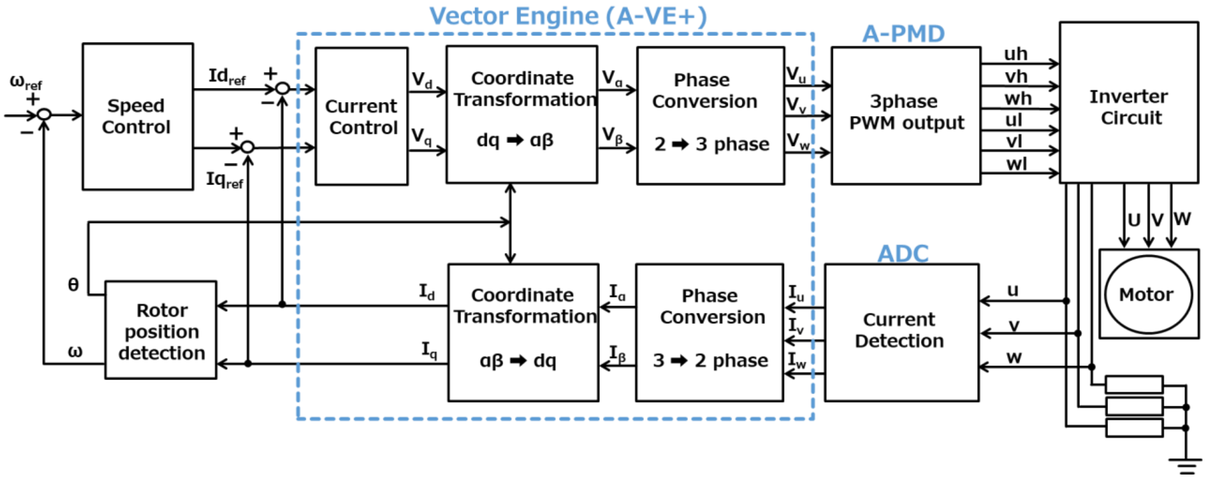


Figure 2: Vector control components and acceleration support in the A-VE

PWM alters the period for which a power transistor used to deliver current remains on, within a fixed clock cycle. When the duty of the pulse width of the switching element is large, the output voltage and output current become large. The high switching rate needed for smooth power delivery across three inverter phases often imposes a high overhead on the CPU, often involving a high interrupt frequency.

The PWM-generation function also needs to take into account factors such as inserting dead time when phases are switched, as well as taking care of handling fault signals that indicate potential problems. This often imposes a high overhead on processing through frequent interrupts from peripherals to the processor core. Toshiba's Advanced Programmable Motor Driver (A-PMD) can take over most of the high-frequency PWM operations from the host CPU.

The A-PMD unit combines a wave-generation circuit with a synchronous trigger-generation circuit. Across three phases, the wave-generation circuit generates appropriate PWM signals within each cycle. To do this, the unit includes hardware circuitry that eases overall system design. As well as providing protection functions to ensure safe operation in the event of faults and support for dead-time insertion, the A-PMD adds phase-shift functionality. This provides accurate timing signals for all three phases using the data from just one current shunt.

By employing the Arm® Cortex®-M4 RISC-based processor core running at speeds of up to 160MHz, together with 12bit ADC channels, the TMPM4KL provides the headroom to control not just two motors using FOC but also controls the boost PFC, provides commands to a pump-motor controller and an array of solenoid-operated valves. Three on-chip A-PMD units provide PWM control to the compressor and fan motors as well as the boost circuit. This combination of a core processor with dedicated accelerators, and tightly connected peripherals optimises the software for throughput and minimises the interrupt load. Accurate control loop support is aided by the way in which the architecture synchronises ADC captures with the motor timer.

Built-in safety features ensure reliable operation under fault conditions, with protection from overvoltage and overcurrent events. Parity on RAM and error correction on flash in combination with abnormal clock detection circuitry ensures the system is not compromised by interference corrupting code or data transferred across system buses. Together with firmware and software support, the design allows for cost-efficient single-shunt current measurements, effectively reducing the time to market.

The RD219 reference design is built around the TMPM4KL and provides the components needed to implement control for the key building blocks of a typical heat pump, including the valve outputs, and an efficient PFC implementation. The technique used for PFC in the RD219 is the continuous-conduction mode (CCM) to provide lower current ripple than other PFC techniques. The use of an IGBT such as the fast switching GT30J65MRB, with low forward conducting voltage helps ensure low losses. The PFC design is augmented by the TRS24N65FB silicon carbide (SiC) Schottky diode, which combines low stored charge with reduced forward voltage for low conduction losses in the on-state.

In the compressor section, the TK20A60W5 600V DT-MOS MOSFET provides a super junction structure for low conduction losses together with low parasitic capacitances for fast and efficient switching. Its optimised body diode structure leads to low diode-recovery losses in hard switching application like motor control. A fully isolated TO-220SIS package simplifies heat-sink mounting.

For fan control, the TPD4204F intelligent power device integrates a level-shifting gate driver IC with superjunction MOSFETs, providing low conduction and switching losses when providing power to the motors. The use of a small, standard package leads to a cost-efficient and space-saving PCB design. Control over additional motors can be provided with sensorless sinusoidal control using the TC78B011FTG motor control driver.

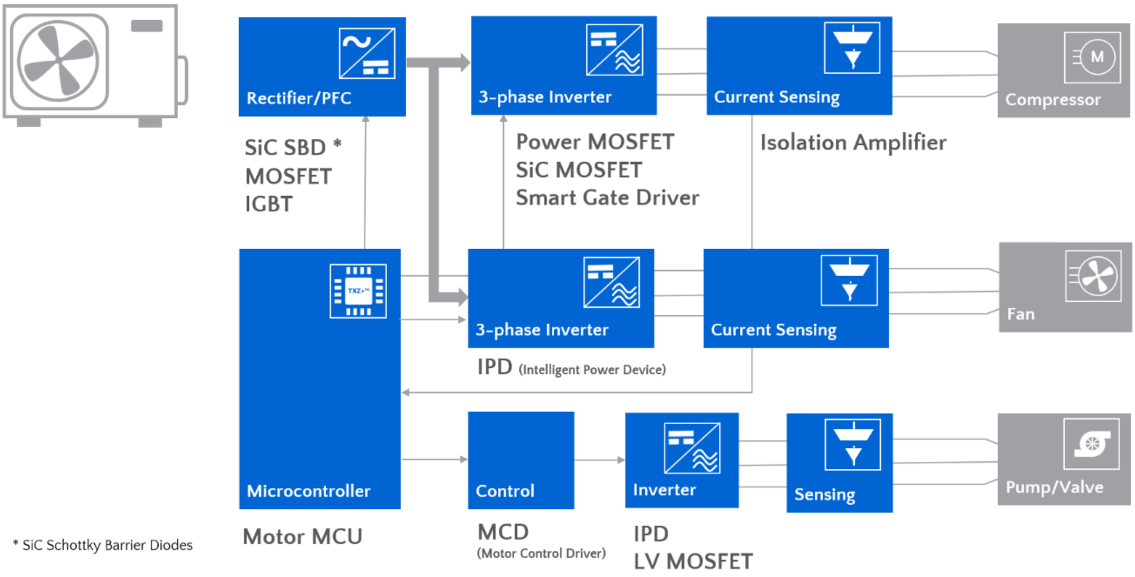


Figure 3: Key components in a heat pump design

Where the 1300W of output power for the compressor motor is not enough, Toshiba also provides for an efficient compressor drive reference design for large residential or commercial buildings. The RD220 reference design provides an example of the way in which novel transistor technologies can improve system efficiency in higher power applications up to 18kW. It relies on 1200V SiC MOSFETs for less switching losses and lower conduction losses in partial and full load conditions, compared to the traditionally used IGBTs in this power class.

Conclusion

Though there are many parts to a heat pump that require precise control to maximise efficiency and deliver the required coefficient of performance, this does not necessarily call for the use of multiple cooperating MCUs. A standard MCU processor core such as Arm Cortex-M4 can provide the execution bandwidth to coordinate the operation of motors, PFC, and valves within the pump thanks to the addition of accelerators designed to support these complex, real-time tasks. In doing so, the architecture supports a smaller bill of materials, simpler programming and easier manufacturability while helping to maximise efficiency through FOC and high-performance PFC techniques.

References:

Air Conditioner Outdoor Unit Control Circuit – complete reference and design information pack:
https://toshiba.semicon-storage.com/eu/semiconductor/design-development/referencedesign/detail.RD219.html

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