Application Note

Design Considerations for Automotive PTC Heater Modules

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ABSTRACT

The transition from Internal Combustion Engine (ICE) vehicles to electric vehicles (EV) comes with a lot of opportunities and challenges. It is crucial for automakers to make EV subsystems and end vehicles that are efficient and cost-competitive to ICEs if they want mass adoption of their product. Increasing overall subsystem efficiency helps maximize drive range, and optimizing costs throughout the supply chain makes EVs attractive to the end user. A system that automakers must learn how to make more efficient and cost-effective is the thermal management system of the EV. In an EV, the cooling process is similar to the that of an ICE or residential systems via using a compressor to blow cold air through the coolant. However, when it comes to heating, a different approach must be used. ICEs can capture and use heat from the engine to pass through the coolant or directly through the cabin. But when it comes to EVs, there is no engine. And, the traction motor is too efficient to generate enough residual heat fast enough to capture for heating the coolant or cabin. So, one method commonly used to either supply additional heat or take full responsibly of heating the coolant/cabin in EVs is via positive temperature coefficient (PTC) heaters.

Table of Contents

List of Figures

List of Tables

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1 Introduction

PTC heaters generate heat via resistive heating. Current flows through the PTC heating element (thermistor) and generates instantaneous heat to either heat the coolant or the cabin directly, with the heat increasing as more current flows through. Once a specified temperature is achieved, the resistance in the heating element rises significantly. This limits the chance of overheating. This application has the advantage of simplicity of use and system design. The control for this application is responsible for supplying current within the rating of the PTC load over a period of time and shutting off that current once heating is completed. The drawback to PTC heaters is that their Coefficient of Performance (CoP), the ratio of useful heat or cooling to energy needed for said system, can be at most 1:1, as opposed to heat pumps which can achieve a much higher CoP. This is accomplished by the heat pump using the power it gets from the battery to move hot air to and from the outside environment instead of generating the heat like the PTC heater does. So, more heat energy is transferred into the cabin than electrical energy is used to operate the system. The higher CoP results in a longer driving range for the EV, making this system attractive to automakers. However, a designer may still want to use a PTC heater solution instead of/in addition to a heat pump due to its simplicity and cost advantage over a heat pump system. The designer may also deem the PTC heater as a more practical heating system than the heat pump if the EV end user is in a very cold climate. The heat may have to be generated if it is not available in the outside environment of the car.

2 Automotive PTC Heater Module Overview

This section describes the high-level design topologies for full EV heating and cooling systems, as well as topologies for PTC heater control modules at a subsystem level.

2.1 Automotive Heating Architectures

2.1.1 Positive Temperature Coefficient Heaters

A common EV thermal management system topology involves a compressor and heater working together in the same system by splitting responsibilities, as shown in Figure 2-1.

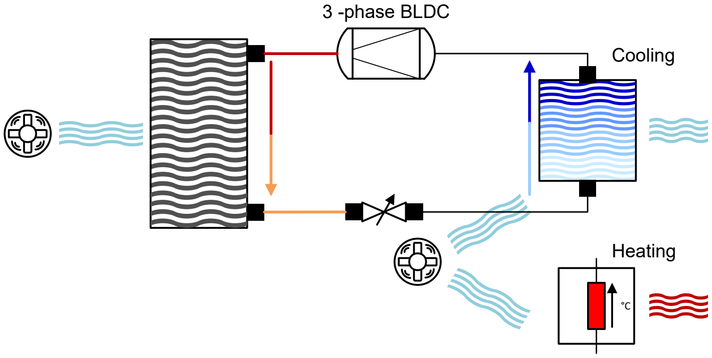


Figure 2-1. EV Thermal Management System With Compressor and Heater Working Together

To cool the cabin, the refrigerant is first heavily compressed, turning it into a very high temperature gas. Then, refrigerant is cooled in the condenser, thus turning it into a liquid and warming the air in the process. Then, the liquid refrigerant enters the expansion valve, decreasing the pressure thus cooling the refrigerant. The refrigerant is then warmed in the evaporator, and the resulting cold air is blown throughout the cabin. When cooling the high voltage battery, a similar method is used, but the chiller is used as a heat exchanger to cool the coolant and transfer it to the battery to cool it.

The PTC is responsible for generating heat. This heat is then spread through the cabin via air from the blower. The pump helps coolant pass though the PTC, to then send to the high-voltage battery to warm it, as shown in Figure 2-2.

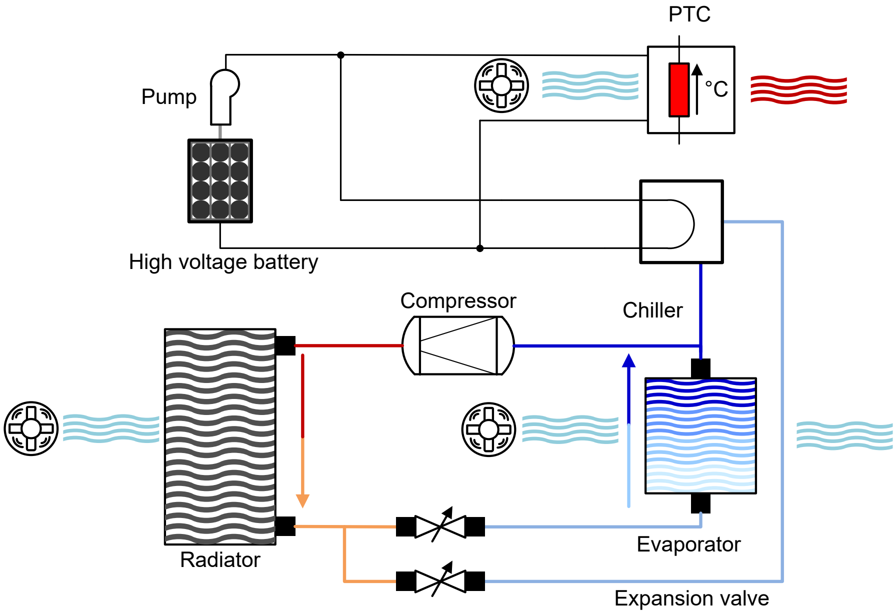


Figure 2-2. PTC Heating Coolant Sent to High Voltage Battery

2.1.2 Heat Pumps

The heat pump is an application that is responsible for both the heating and cooling of the cabin, per Figure 2-3. The method is similar to the aforementioned cooling circuit with a compressor, condenser, expansion valve, and evaporator. However, this can be used in both directions, with either the radiator being used as evaporator to warm in the cabin, or the radiator being used as condenser to cool the cabin. However, the smaller the differential of the ambient temperature and the refringent temperature is, the less efficient the heat pump system will be. So, the higher differential between the ambient environment and refrigerant temperatures, the more efficient the system will be.

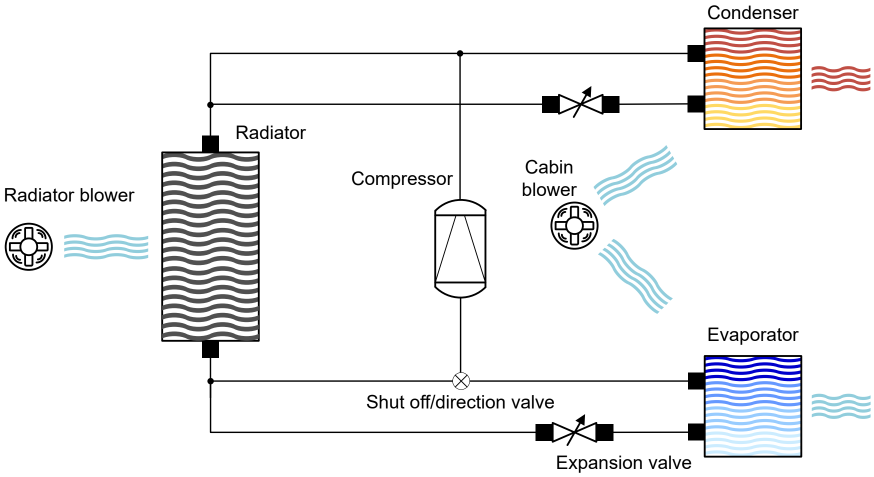


Figure 2-3. Heat Pump System

In order to improve the CoP of a heat pump system, additional heat sources (for example, traction inverter, compressor motor, blower motor, and so forth) can be added into the system, as shown in Figure 2-4. This increased (CoP) would help increase the vehicle's driving range. However, this approach does have its drawbacks, as well. It adds more complexity due to the additional circuitry and connectivity required. It is also heavier as more tubing, refrigerant and/or coolant would be needed.

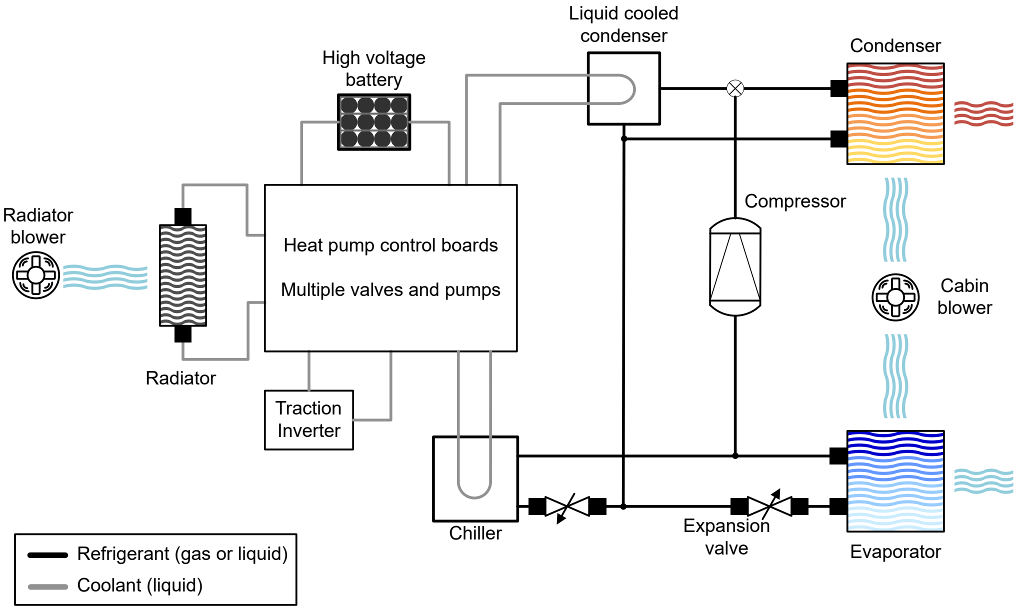


Figure 2-4. Heat Pump System With Additional Heat Sources

Lastly, an EV thermal management method that can be used today is combining the Heat pump and PTC heater systems. This can be used in cases where there is not enough available heat to be captured from outside the vehicle due to cold climate, nor is there sufficient heat from other heat sources. This method helps ensure the end-user stays warm, but it requires a heavier, more complex and more expensive design

2.2 Automotive Heating Architectures

2.3 PTC Heater Topologies

When designing a PTC heater system, a basic consideration that must be made is how many heating elements, or “loads” does your application call for. When designing solely for cost, having one large PTC load can be simpler than using multiple smaller loads. However, when designing for increased functionality and flexibility, having multiple PTC loads may make more sense. Having multiple PTC loads lets the system turn off some power if full power is not needed. Multiple PTC loads can also enable “zonal heating”, which allows heating to be spread out in different areas of the cabin. This also allows for dedicated PTC heating elements for the cabin and the battery. The next sections will lay out the different options for controlling current through the PTC loads.

If the goal of the system is to achieve the lowest cost possible, then consider having a single low side switch under each load and referenced to ground, as shown in Figure 2-5. The main drawback here is that there’s no low-side protection. A short to high can be handled by the low side switches, but there is no way stop power from flowing from battery/DC link capacitor through the PTC loads during a short to low. So, this topology can be used if the system is deliberately designed to rely on the power distribution unit (PDU) for short circuit protection.

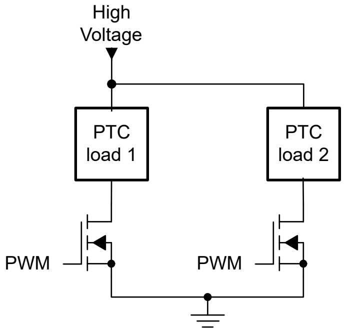


Figure 2-5. Single Low-Side Switch Under Each Load and Referenced to Ground

One method to incorporate short circuit protection would be to utilize the dual low-side topology. This topology includes short circuit (SC) protection in series with the low side switches in order to disconnect them in the event of a short circuit fault in the power switch or the switch driver of either leg, as shown in Figure 2-6. This is relatively low cost as well since it avoids high-side drivers, which tend to cost more. This enables multiple points of failure and disconnect on each leg but cannot protect the system if a short circuit occurs directly between the load and ground.

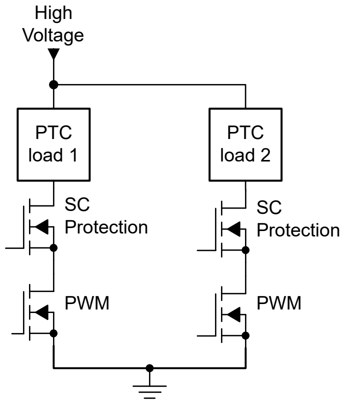


Figure 2-6. Short Circuit Protection in Series With the Low-Side Switches

A method of enabling disconnect from the high-voltage battery is having a single point of SC protection on the high side and a switch on each leg of the low side for regulation, as shown in Figure 2-7. So, the high-side has protection for a short circuit to ground, and the low-side switches offer protection from a short circuit to high. A drawback of this kind of topology is that a PTC fault of one leg will cause both to be disconnected, so the legs cannot be independently controlled or protected.

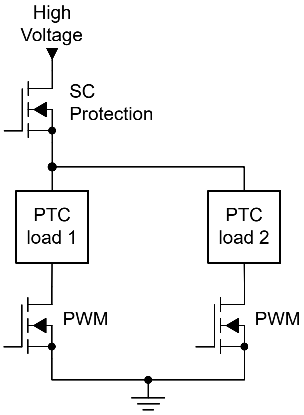


Figure 2-7. Single Point of SC Protection on the High Side and a Switch on Each Leg of the Low Side

Lastly, flexibility can be added to the system by having a point of short circuit protection on both legs, shown in Figure 2-8. This allows for either leg to be controlled independently. This is useful for control of output power or in the case of one PTC load failing.

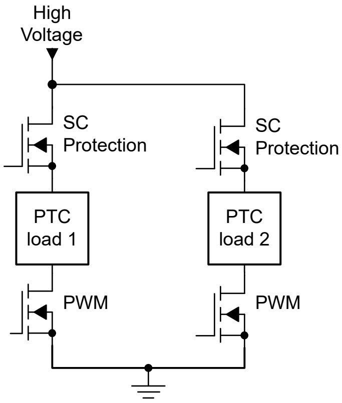


Figure 2-8. Short Circuit Protection on Both Legs

3 Design of Automotive PTC Heater Controller

3.1 Block Diagrams

The main PTC heater control modules topologies mentioned in this guide all have a high voltage side and low-voltage side that are separated by an isolation barrier. The low-voltage side is the portion of the design powered by the 12V rail. The high voltage side is the portion of the design powered by the output rails of the isolated power supply and the high-voltage battery. The following topologies differ by placement of the isolation barrier (denoted by the thick dashed line in the following figures) and the number of microcontroller units (MCUs) used.

One common PTC heater control module topology is having two MCUs, with one on the low-voltage side and one on the high voltage side, shown in Figure 3-1.

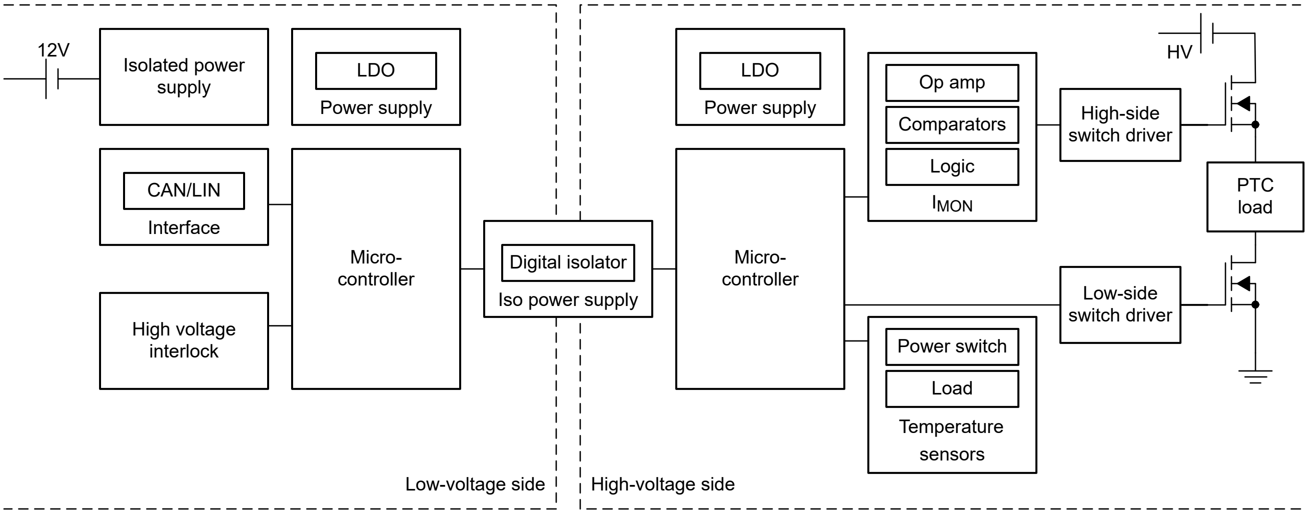


Figure 3-1. PTC Heater Control Module Topology With Two MCUs

The second topology that is discussed in this guide is the use of one MCU for the whole system on the high-voltage side, as shown in Figure 3-2.

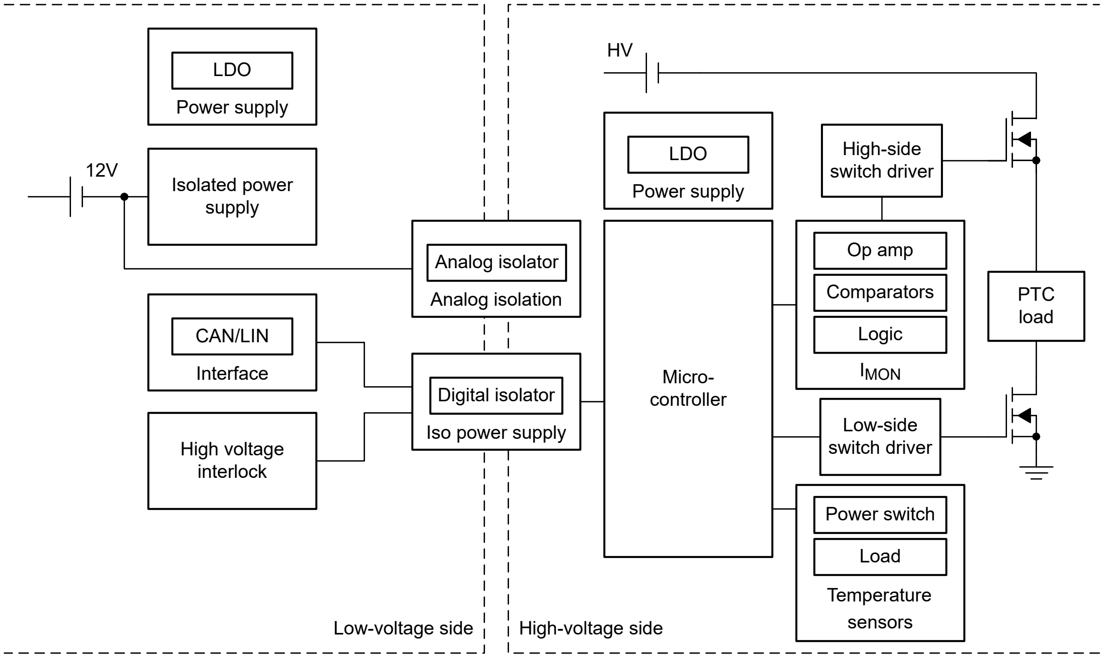


Figure 3-2. PTC Heater Control Module Topology With One MCU on the High-Voltage Side

Another possible topology is the use of one MCU for the whole system on the low-voltage side, as shown in Figure 3-3. This is an uncommon topology due to the added cost of implementing multiple analog and digital isolators, so it is not discussed further in this guide.

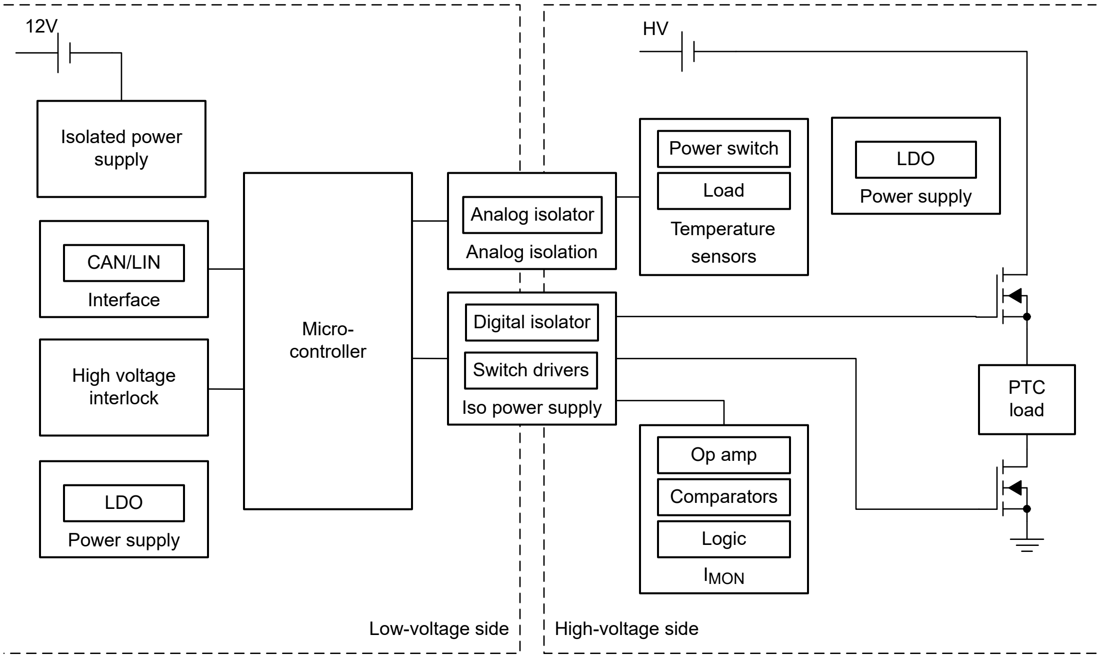


Figure 3-3. PTC Heater Control Module Topology With One MCU on the Low-Voltage Side

The advantages and drawbacks for these topologies in regard to the needed components are explained throughout the rest of Section 3.

3.2 Designing the Power Supplies

The purpose of the isolated power supplies in this system is to take the input voltage from the low-voltage side and create a well-regulated output for the components on the high-voltage side while creating an isolated barrier via galvanic isolation between the high-voltage and low-voltage sides of the PTC system. The operating range of the low-voltage input is often around 6V to 16V, while the absolute maximum range can be around 4V to 42V. The designer can ensure that output voltage of the power supply outputs are high enough to satisfy the power supply inputs of the switch drivers. The required output power is dependent on the power needed to drive the power switches as well as power the MCU(s), sensors, comparators and so forth. The output voltage chosen by designers tends to be around 15V to 20V. There are typically two output rails (one high-side and one low-side), but a third output rail can be used to power the lower voltage components (for example, MCUs, sensors, op-amps). A lower voltage output rail can also enable the designer to use a less expensive LDO.

Regardless of the power topology used in the PTC heater module design, an input filter circuit may be needed to feed into the rest of the power supply in order to help it meet EMI requirements. The input filter circuit may have to be edited and customized to fit the characteristics of the specific PTC heater design. Figure 3-4 shows the circuit for the typical undamped input filter, for example. For guidance on designing an input filter, *Input Filter Design for Switching Power Supplies* is a good resource.

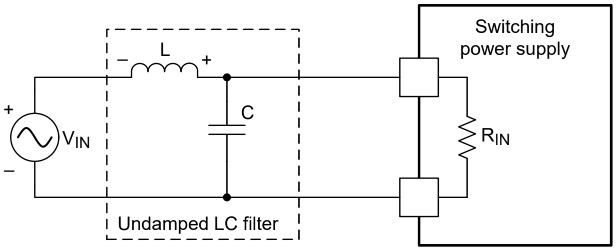


Figure 3-4. Typical Undamped Input Filter

There are plenty of isolated power topologies a designer can choose from, but the main topologies suitable for PTC heater modules are flyback, LLC and push-pull topologies. Other power supplies may not be recommended because the intended power output for these topologies typically exceeds what is needed for PTC heater control modules. The flyback converter, shown in Figure 3-5, may be the most common topology used in automotive applications due to its simplicity and versatility.

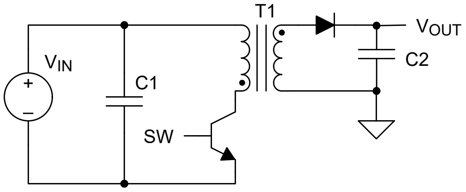


Figure 3-5. Flyback Converter

Flyback converters can accept a wide range of input voltages, making them suitable for the operating and absolute maximum ranges of the input voltage of the PTC heater module without a pre-regulator. Flyback converters can also supply multiple output voltages, so they can support the one or two rails typically needed in this application. These output voltages can all be regulated with a single control, being the duty cycle. The output voltage can be calculated with Equation 1:

$$V_{out} = \frac{N2}{N1} \times \frac{D}{1-D} \times V_{in} \tag{1}$$

Since the required output rail voltage is not many magnitudes higher than the input voltage, the transformer turns ratio in the flyback can be relatively low. It is recommended that the turns ratio are to be picked such that the maximum duty cycle will not be higher than 50% at V_{IN} min. Depending on what is the ratio between the two output rails, the designer may have to get a custom transformer since it is not possible to get a perfect turns ratio transformer in the broad market.

Transformer drivers can simplify the design by integrating components of a power supply system into one integrated circuit (IC). One type of transformer driver is a controller, a component responsible for driving the primary side switch of the flyback circuit at the correct duty cycle, the feedback mechanisms needed in the power supply circuit, under-voltage lockout for the input voltage, and possibly overcurrent protection. This topology can be seen in Figure 3-6. An advantage of using a controller is that the designer can control the slew rate used to drive the primary side switch with an external resistor on the gate. This can help control induced EMI. Another benefit is that the designer has the flexibility to choose the switch individually, enabling more current to be driven if necessary. Some systems may also prefer controllers as they grant the designer the flexibility to put the primary side switch on areas of the PCB that are less likely to cause thermal issues. A suitable controller for this application would be the LM34966-Q1 due to its wide input range of 2.97V to 40V (absolute maximum rating of -0.3V to 45V), enabling this device to withstand automotive load dump and cold crank conditions.

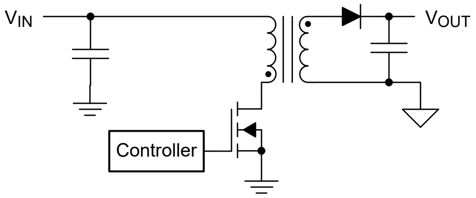


Figure 3-6. Controller Topology

Another transformer driver type is the converter, which comes with the same benefits as a controller and the switch integrated to help shrink and simplify the design while reducing cost, as shown in Figure 3-7. However, integrating the switch does prevent the ability to adjust slew rate and controlling EMI induced by it. A converter that can be suitable for flyback applications is the LM25180-Q1 due to its wide input range of 4.5V to 42V (absolute maximum rating of -0.3V to 45V). This device also integrates the auxiliary winding, offering primary side regulation (PSR) for the power supply design, thus simplifying the design of the transformer.

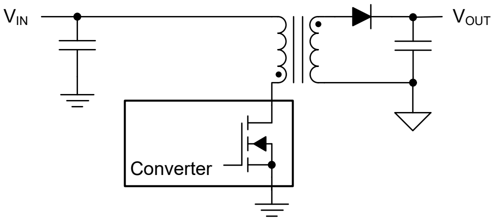


Figure 3-7. Converter Topology

To help improve EMI and decrease the cost of the transformer needed in the PTC heater module design, a designer may opt to use an LLC topology (see Figure 3-8) instead of a traditional flyback design. An LLC can help increase efficiency by using resonant switching, which is switching involving inductors and capacitors to create sinusoidal currents and voltages during the switching periods. This method helps eliminate switch transition losses, thus increasing efficiency. There is also low parasitic capacitance in this kind of topology and great EMI mitigation, thus enabling the designer to use a cheaper transformer than they would in a flyback converter. However, this topology is an open loop, so variations on the input or output won't have a controlled response. Another functional disadvantage of LLCs is being open loop is that they cannot take a range of input voltages like flyback converters, so they will need a pre-regulator IC like the LM5157-Q1. Converters are also widely used to help simplify LLC designs. A great choice for an LLC converter would be the UCC25800-Q1 as it can help reduce EMI even more by enabling soft-switching.

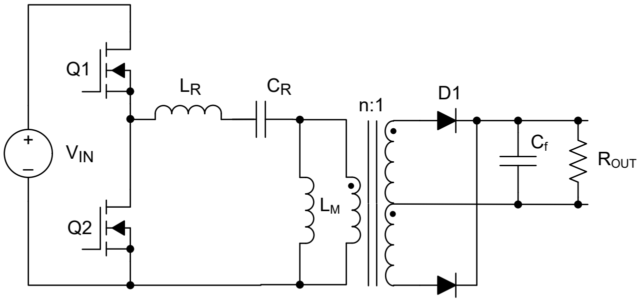


Figure 3-8. LLC Topology

Push-pull topologies are also suitable for several high voltage automotive applications, including PTC heater control modules. Unlike a flyback converter, which stores energy in an inductor in one phase of the switching cycle and send it to the load in the other phase, push-pull converters use transformer action to transfer power from the primary side to the secondary side. Their topology can be seen in Figure 3-9.

This is done without analog feedback or loop stabilization. It is also an open loop configuration, so it does not need feedback, simplifying the design. A disadvantage that push-pull topologies have is that they lack load regulation. One of key advantages of push-pull topology is the simplified transformer design. Center-tapped transformers are readily available with various turns-ratio avoiding the need for designing a custom transformer. Many a times, you can also find transformers with multiple outputs readily available and if they are not available, designing the transformer is relatively simple involving only two key parameters, the minimum V-t product and turns-ratio. The data sheets of these devices include list of readily available transformers from multiple vendors for the most commonly used input/output voltage rails.

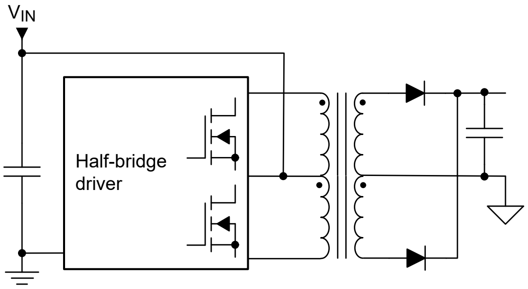


Figure 3-9. Push-Pull Converters

Converters can also be used to help shrink and simplify push-pull designs. The SN6507-Q1 meets the requirements for most high voltage automotive applications as it offers large input voltage (60V absolute maximum) and line regulation.

The SN6507-Q1 can be used for isolating lower voltage logic rails for powering isolators. Using localized isolated power solutions for individual isolators also simplifies the primary isolated power solution's design while also helping a simpler PCB layout design.

DC/DC modules can be used in PTC heater modules, as well. They integrate the primary side switch and the transformers of the power supply, significantly reducing board space and height as well as simplifying system design (see Figure 3-10). DC/DC modules drastically reduce the number of discrete components needed. These ICs also come with an integrated isolation barrier. DC/DC modules can also help make it easier to implement a distributed power supply architecture, which involves having one power supply per switch driver. This increases system reliability by providing multiple point of loads allowing independent point of failure detection. So, if one power supply fails, the rest of the system can still operate. With this kind of solution, however, the designer may need to implement a pre-regulator if the input voltage range exceeds the DC/DC module's absolute maximum ratings. The individual IC cost is relatively higher than converter ICs, but the commercial benefits come in the total system cost saved by integrating so many components. These ICs tend to be less efficient, but a significant amount of design time is saved since several discrete component calculations and considerations do not need to be done. A good choice for a DC/DC module in a PTC heater module would be the UCC14141-Q1, especially if the PTC heater module is using an 800V or higher battery due to this DC/DC module's 5kV$_{RMS}$ isolation rating. It also provides the designer with a very low-profile isolated power supply solution of 3.55mm in height.

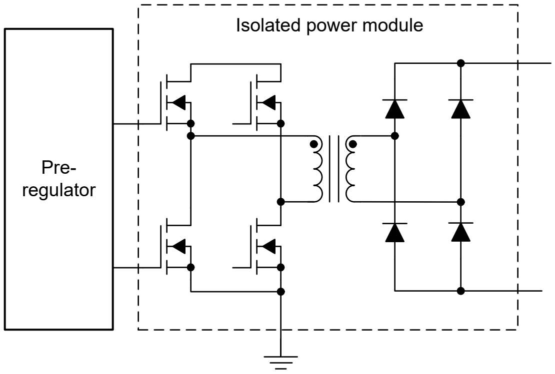


Figure 3-10. DC/DC Module Topology

3.3 Picking Low-Dropout Regulators

The low dropout (LDOs) regulators in this system are meant to step down voltage from the low-voltage and high-voltage rails and provide clean power rails to the components on both sides at the correct respective voltages. Specifically, for PTCs heater designs, they can power the communication interface, digital isolator and MCU on the low-voltage side, as well as the switch driver(s), load current monitoring circuit, temperature sensors and MCU on the high-voltage side.

If the designer wants an LDO connected to the input voltage rail, this device must be able to handle the input rail's absolute maximum voltage range (around 4V to 42V) in the cases of cold crank or load dump. In regard to powering an MCU, TI recommends that the LDO has low quiescent current (I_Q) to optimize power efficiency. A suitable LDO for PTC heaters would be the TPS7B84-Q1, with its wide input range of 3V to 40V (-0.3V to 42V absolute maximum range) and maximum I_Q of 35μA. For more guidance on designing with LDOs, the LDO Basics (Rev. A) eBook is a great resource.

The designer may have to use an off-board temperature sensor to get a more accurate reading of the PTC load temperature. If the power supply used for this temperature sensor is different than the reference voltage for the analog to digital converter (ADC) used to take in the sensor reading, then variation of the sensor power supply and the ADC reference voltage can cause significant ADC output variance, resulting in errors. One way to resolve this issue is by tying the temperature sensor power supply and ADC reference voltages together, but because this involves long cable connections, this method introduces an increased likelihood of fault conditions.

The designer can eliminate these issues by using a tracking LDO so that its output to the off-board temperature sensor and the ADC reference voltage are within a specified margin of each other. Figure 3-11 shows an example block diagram of its implementation.

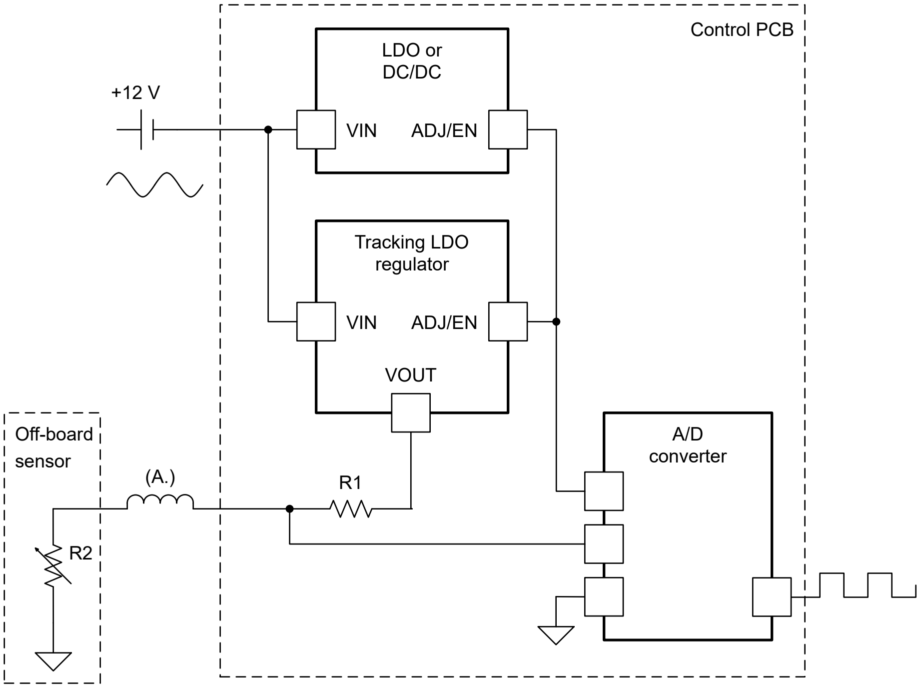


Figure 3-11. Off-Board Temperature Sensor Implementation

A suitable tracking LDO for this application would be the TPS7B4254-Q1, as it includes this ratiometric tracking feature with ±4mV output-tracking tolerance. It is also designed with integrated protection features for system robustness against fault conditions, including reverse current protection, reverse polarity protection, and more.

3.4 Designing of the Communication Interface

The purpose of the communication interface is to communicate commands and information back and forth between the CAN/LIN bus and the PTC heater module. CAN is a multi-drop, differential communication bus with a data rate up to 5 Mbps which connects multiple nodes in the vehicle while LIN is a single-wire, supply-level interface that communicates at 20kbps. The PTC heater module subsystem may receive signals directing it to supply current to the loads and temperature settings from the bus. Similarly, it may relay power status, temperature settings and fault information back to the network. The data rate and wiring requirements for relaying the information and commands sent to and from the PTC controller can typically be handled with a LIN transceiver.

If the designer needs to have a LIN with a designated WAKE pin, the TLIN1021A-Q1 can be used. If a designated WAKE pin is not needed, the TLIN1029A-Q1 is certainly suitable.

System basis chips (SBCs) are transceivers with integrated power supplies to help reduce system component count and possibly lower total system cost. Having the power supply of the transceiver integrated can eliminate the 12V to 3.3V/5V stage in a PTC heater module. An SBC that can be used in PTC heater modules is the TLIN1028-Q1, which is an integrated LIN transceiver and LDO.

For guidance on best practices of implementing a LIN transceiver into the system layout, the designer can look at the LIN Protocol and Physical Layer Requirements. All LIN transceivers that were suggested previously in this section come in SOIC or VSON packages. A designer can select a leaded or leadless package option based on design requirements. If the designer wants a LIN transceiver with leaded packaging, but has the space advantage of the VSON package, they can pick a device that comes in SOT, like the TLIN1039-Q1.

3.5 Implementation of the Digital Isolator

The purpose of the digital isolator is to relay information back and forth between the low voltage side and high voltage side of the PTC control module, while providing galvanic isolation between these two sides.

The designer must determine how many signals need to be sent to and from the high voltage side, as well as what signals those will be. The more signals that need to be sent over the isolation barrier, the more channels in the digital isolator are required. The amount and type of signals needed to pass through the isolation barrier are also highly dependent on the topology of the subsystem in regard to the MCUs. Guidance regarding the selected MCU topology can be found in the "Implementation of the microcontroller unit" from Table 3-1.

The EV battery voltage can have an impact on what isolation rating (VISO) you need your digital isolator to have. For up to 400V, basic (3.0kV$_{RMS}$ to 3.7kV$_{RMS}$) or reinforced (5.0kV$_{RMS}$ to 5.7kV$_{RMS}$) isolation is suitable. For 800V, however, reinforced isolation tends to be more commonly implemented. Creepage and clearance is also impacted by battery voltage and what standards (IEC, UL and so forth) the design must adhere to. If higher creepage and clearance is needed, there are digital isolators whose package's creepage could fit said requirement. For example, if a very wide creepage distance is needed, the designer could select the ISO7741-Q1. This device can come in the DWW package (10.30 mm × 14.0 mm). However, PTC heater modules tend to not need this wide of a creepage, so the designer can pick a device like the ISO6741-Q1 with DW package (10.30 mm × 7.50 mm).

When placing the digital isolator block in the PCB layout, the designer can use the *Digital Isolator Design Guide* for comprehensive guidance. To help reduce the PCB area, a designer can pick a digital isolator with an integrated power supply to eliminate the need for a component powering either the primary or secondary side of the device. This can also reduce total system cost depending on if there would have been a dedicated power supply for powering either side of the digital isolator, and how much that dedicated power supply would have cost (for example low-drop out regulator) A digital isolator that can offer this kind of benefit is the ISOW7741-Q1. This device has an isolated DC/DC converter integrated in it, eliminating the need for a discrete isolated power supply for the secondary side of the isolator.

3.6 Implementation of the Microcontroller Unit

The microcontroller unit is meant to either relay signals and commands to or take in signals and measurements from different components in the PTC heater control module. They will take signals indicating how much current is to be supplied to the PTC, what temperature the PTC load is be at, and relay commands to the respective components. The MCUs also take in measurements such as temperature, voltage, current and so forth and commit to appropriate actions with respect to those measurements and conditions. The specific signals it sends or receives depends on how many MCUs are present in the design, and whether the MCU is placed on the high-voltage side or low-voltage side.

If the designer chooses to use 2 MCUs, one on the low-voltage side and one on the high-voltage side, the MCU on the low-voltage side is in charge of communication, while the MCU on the high-side is in charge of PTC load control. This topology results in minimizing the number of isolated signals needed.

If the designer decides to use one MCU and place it on the high-voltage side, it is recommended to then have a LIN transceiver without a dedicated WAKE pin to limit signals that need to transferred from the high-voltage side to the low-voltage side. However, if the designer wants the low-voltage rail to be monitored by the MCU to sense if it goes outside of the operating range, that signal can go through a high precision analog isolator, then feed into the MCU. A suitable analog isolator for voltage sensing this application would be the AMC1336-Q1 with its great DC performance of ±0.5mV maximum offset error. It also comes in small DWV (5.85mm × 11.5mm) package. Another option would be to use a discrete comparator circuit to detect when the input voltage rail goes outside of the operating range, and have that signal go through a digital isolator, then to the MCU. The TLV3201-Q1 could be suitable for this purpose. It is recommended that the MCU process enough pins available for connections to the digital isolator, the switch drivers, the temperature sensor(s), the load current monitoring circuits and voltage follower. There is no direct impact on MCU selection when designing with either a 400V or 800V battery. This topology can be used to save cost given the limited isolated signals needed and the use of only one MCU.

Table 3-1 lays out an example of what signals the MCU could send or receive depending on topology and placement. Some signals can be added or removed based on the discretion of the designer.

Table 3-1. Signals the MCU Could Send or Receive Depending on Topology and Placement

Two Microcontrollers (1 on the high-voltage, 1 on the low voltage side)	
High-voltage side MCU	Send • Switch drivers EN pins • Switch driver's inputs • GPIO’s between MCUs Receive • Load current measurement • Power switch temperatures from temperature sensors • PTC load temperatures from temperature sensors • DC Bus voltage from voltage feedback circuit • Power switch short circuit faults • Overcurrent circuit RST
Low-voltage side MCU	Send • TXD to transceiver • EN to LIN transceiver Receive • RXD from transceiver • Input voltage from Low voltage input rail • Interlock
One Microcontroller on the High-Voltage Side	
MCU	Send • Switch drivers EN pins • Switch drivers inputs • EN to digital isolator • TXD to digital isolator Receive • Load current magnitude • Power switch temperatures • PTC load temperatures • DC Bus voltage (via voltage feedback) • Input voltage rail signal from analog isolator • Power switch short circuit faults • Overcurrent circuit RST • RXD from digital isolator • Interlock

Interlock is a current and voltage loop mechanism that connects all high-voltage subsystems in the vehicle (battery management systems, traction inverters, on-board chargers, and so forth). It monitors any interference or tampering done on these subsystems or to the service disconnect switch. If this condition is detected, then the high-voltage subsystems in the vehicle, such as the PTC heater module, will shut down. Including the PTC heater module in the interlock mechanism increases safety by decreasing the risk of damage to the user and other subsystems. For guidance on how to design the interlock mechanism, see TIDA-01445.

The choice of using one or two MCUs varies from designer to designer. Either of these topologies are used in PTC heater modules across the market, so there is no right or wrong choice. The designer just needs to understand the advantages and drawbacks of each, and select the topology that aligns best with the goals and requirements of their system. An MCU suitable for PTC heaters is the TMS320F2800153-Q1, which comes with 64KB of flash size in 32-pin RHB (5mm × 5mm) or 48-pin PHP (9mm × 9mm) packages. The 48-pin version has more analog and GPIO pins than the 32-pin version, so it is up to the designer to decide which version to use. It may make more sense to use the 48-pin version if the design calls for 1 MCU. However, a 2 MCU approach may make more sense to use 32-pin MCUs. Another viable option would be the MSPM0L1305-Q1, a 32-pin RHB (5mm × 5mm) MCU with a 32-Mhz Arm® Cortex®-M0+ processor core. Having an Arm Cortex-M0+ core enables optimized power efficiency and high performance. This device also fits well within a PTC heater due to its LIN communication support.

3.7 Designing of the Switch Driver Stage

The purpose of the switch driver in this application is to pulse width modulate (PWM) the power switches so current can be supplied into the load, and turn them off to stop load current when commanded to do so. Switching frequencies (F_{SW}) of PTC heater applications usually can go up to 20kHz. The high-side switch driver must also operate at 100% duty cycle. There are two solutions that can accomplish turning on and off the power switches. This can be done with either a gate driver or solid-state relay, both come with their benefits and drawbacks.

If gate drivers are selected as the switch driving method of choice, then the designer has the flexibility of using either single channel gate drivers (can drive one power switch) or dual-channel gate drivers (can independently drive two power switches). Using a single channel driver enables the placement of the gate driver to be close to the power switch to reduce ringing in the gate loop. Dual-channel drivers, however, enable lower total system cost and smaller PCB area. For example, if the design has one load with a high-side switch and low-side switch, then it can either use 1 single-channel gate driver per power switch, or 1 dual-channel gate driver to drive both power switches. However, if the design has two parallel loads, two high-side and two low-side switches, then one has the following options:

- One single-channel driver per power switch (see Figure 3-12)

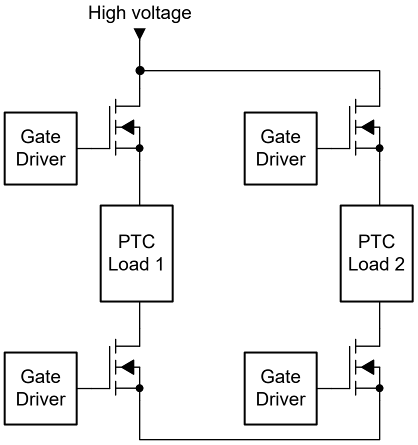


Figure 3-12. One Single-Channel Driver per Power Switch

- One dual-channel gate driver driving the high-side and low-side of each leg, given that the gate drivers' dead time control function can be disabled, and that the channel-to-channel creepage distances are wide enough per system requirements (see Figure 3-13)

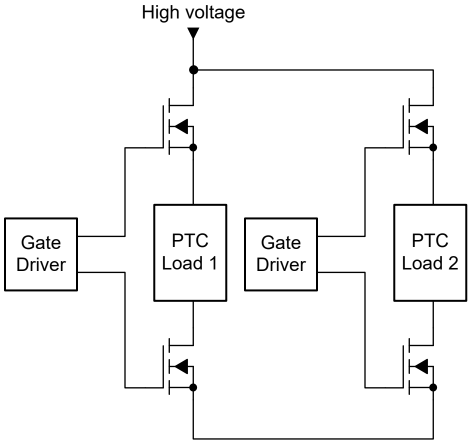


Figure 3-13. One Dual-Channel Gate Driver Driving the High-Side and Low-Side of Each Leg

- One dual-channel driver for the two high side switches and one dual-channel driver for the two low-side switches (see Figure 3-14)

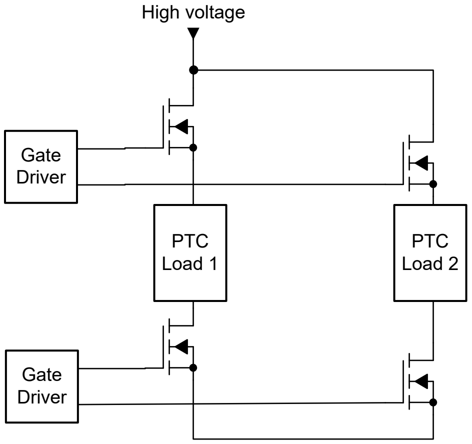


Figure 3-14. One Dual-Channel Driver for the Two High-Side switches and One Dual-Channel Driver for the Two Low-Side Switches

Knowing the recommended range for the switch gate-source (or base-emitter) voltage allows us to determine the correct under voltage lockout (UVLO) for the gate driver. Generally, TI recommends that a designer picks a gate driver with a UVLO of about 3V under the recommended gate-source voltage to account for variations in supply and switching transients and ensure efficient switching.

Gate drivers can assist in turning off the power switches safely in the event of a short circuit fault in the load. This can be done either through a discrete load current monitoring circuit, explained in Section 3.10, or with overcurrent detection integrated in the gate driver itself. Integrating this feature in the IC can reduce overall PCB area and cost.

Gate drivers can also come with galvanic isolation. The recommended isolation rating for the gate driver is based on the battery voltage used, whether the gate driver is placed on the high-side or low-side, the location of the isolation barrier with respect to the human, and other safety mechanisms used within the system. Creepage and clearance is also impacted by battery voltage and what standards (IEC, UL, and so forth) the design must adhere to. Depending on the battery voltage, the high-side may need an isolated gate driver as they can handle a higher working voltage.

A dual-channel isolated gate driver suitable for PTC heaters would be the UCC21551-Q1 as it comes with a DWK package (10.3mm × 10.3mm) option. This offers 3.3mm of creepage between its channels, which is sufficient channel-to-channel creepage distance for automotive applications up to 800V, as well as 8mm creepage from the input side to the output side. If a single channel isolated gate driver is required due to ether topology or creepage needs, the UCC5350-Q1 can fit. It comes in basic isolation options within an 8-pin D package (4.9mm x 6mm) and a reinforced isolation option in an 8-pin DWV package (5.85mm x 11.5mm). This device series also comes with integrated miller clamp options to help prevent false turn-on of the power switch.

A suitable low-side driver could be the UCC27531-Q1 as its strong sink drive strength capability (5-A) makes it compatible with most low-side power switches in high-voltage applications. It also comes in a very compact 6-pin DBV package (2.9mm x 2.8 mm). If a dual-channel low-side driver is desired, then the designer can choose the UCC27624-Q1. This device has dedicated enable pins for both of its channels' inputs, which allows the designer to keep one low-side power switch off in the case of failure while controlling another with the same gate driver.

When it comes to placing the gate driver in the board layout, the designer can reference the following best practices. The gate driver may be placed as close as possible to the power switch to reduce the length of the high-current traces between gate driver and the gate of the power switch. This may be easier with single-channel gate drivers than dual-channel gate drivers. More detailed layout best practices can vary between gate drivers, with information typically available in their respective data sheets.

Solid state relays are a suitable option for driving switches in this type of application. If selected as the switch driving method of choice, then the designer can potentially reduce PCB area and complexity, save on cost, and use a solution suitable for typical PTC heater module switching speeds.

Using solid state relays offers a designer the ability to eliminate some discrete components such as the secondary side power supplies. If using a solid-state relay on the high side of the PTC load, one winding of the isolated power supply can be eliminated, and output power needed is decreased. This also reduces PCB area and system cost.

Similar to gate drivers, solid-state relays can also turn off the power switches in the event of a short circuit fault in the load. This can be done either through a discrete load current monitoring circuit, explained in Section 3.10, or with overcurrent detection integrated in the solid-state relay itself. Integrating this feature in the IC can reduce overall PCB area.

Solid state relays can include galvanic isolation, as well. The guidance for determining necessary isolation rating is the same as it the guidance for isolation rating in gate drivers. A solid-state relay suitable for PTC heaters is the TPSI3052-Q1. Since it has reinforced isolation, it can handle most typical high-voltage battery levels for PTC heaters. It also generates its own secondary power supply, which helps simplify the required isolated power supply circuit, and thus simplifying the overall design. This device fits these features and more in an 8-pin DWZ package (7.5 mm × 5.85 mm).

The cost savings solid state relays have over gate drivers in this kind of application are variable and dependent on the components in consideration for the design. For example, an isolated gate driver combined with the extra winding in the isolated power supply needed to power it may be lower cost than a relay.

3.8 Selection of the Power Switches

The purpose of the power switches is to supply and regulate current to the PTC load. Current being cut off from the PTC load can either be due to the user turning off the vehicle heating system, a short circuit fault on the PTC load, a fault in the switch driver, or a fault in one of the switches themselves.

High-voltage automotive applications tend to use at least one of the three power switch types: Silicon metal-oxide field effect transistor (Si MOSFET), insulated-gate bipolar transistor (IGBT) and Silicon Carbide metal-oxide field effect transistor (SiC MOSFET). Gallium Nitride (GaN) is also emerging in some automotive applications depending on the battery voltage used. Since PTC heaters are typically rated for at least 5kW of output power, they exceed the limitations for traditional Si MOSFETs. So, there are really two choices to choose from: IGBT and SiC. The breakdown of the power switch type in regard to the power level is suitable for can be seen in Figure 3-15. SiC and GaN are great for applications that switch at high frequencies. However, switching losses are not critical to mitigate in PTC heaters. In addition, fast switching can introduce more EMI in the system, which is a much more important factor to mitigate in the PTC heating systems. SiC and GaN are also significantly more expensive than IGBTs, which are currently the most suitable solution for PTC heaters.

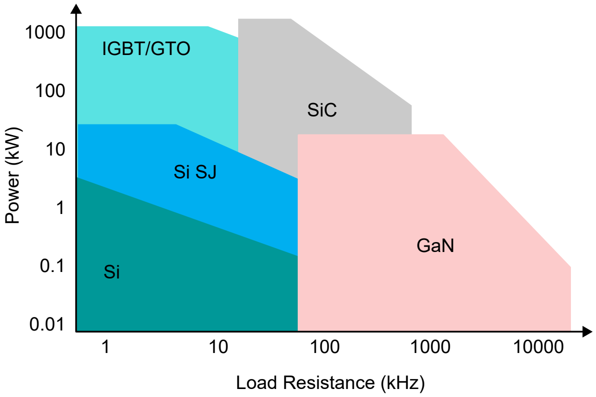


Figure 3-15. Power Level Capabilities Based on Power Switch

IGBTs are popular for high-power applications that operate at switching frequencies ranging from 5kHz to 20kHz, so they are compatible in typical PTC heater control module designs. IGBTs tend to have very low ON-resistances, enabling low-conduction losses, thus good efficiency.

The current going through the power switches depends on the impedance of the PTC load at that time and the high-voltage battery level. For the high-side switch(es), the designer must select a power switch that is rated for the high voltage battery level. It is recommended that power switches are rated higher than the maximum current that is expected to go through their respective PTC loads. This can be determined by dividing the battery voltage by the minimum resistance possible of the PTC load under normal operation. To understand when a typical PTC load is expected to be at minimum impedance, see Section 3.9.

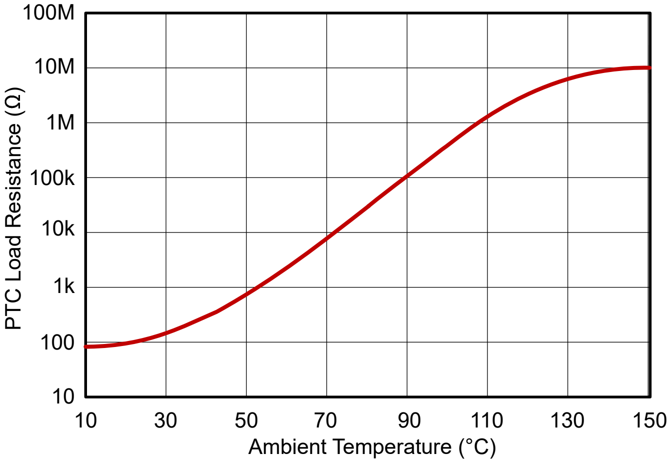
A major decision the designer must make when designing the power switch into the application is how much drive strength is needed to be delivered from the switch drivers. There are multiple factors involved in this: power switch turn-on and turn-off time, efficiency and voltage overshoot risk mitigation. Having a higher peak drive strength will turn on the power switch faster since the gate threshold of the power switch will be reached sooner, also resulting in lower switching losses. The designer may want to consider the implications of increasing the drive strength, though. Too large of a change in drain-source voltage over time can put the power switch at risk of voltage overshoot induced by the parasitic inductances in the system. It is recommended that the drive strength is at a level at which risk of this condition is mitigated. Lowering the drive strength reduces the risk of V_{DS} overshoot, as well as reduces ringing of the gate-source voltage (V_{GS}) and radiated noise of the power switch. However, the rise time for the power switches in the system is mitigated by the resistance of the PTC load, so some degree of voltage overshoot is inherently mitigated by the application. Lower drive strength, on the other hand, can result in higher switching losses. To reach the appropriate drive strength needed for the power switch, the designer must do some testing to get the right balance between system efficiency, timing and risk mitigation.

In addition, the designer must consider the power needed to drive the gate of the switch, power dissipation ratings of the switch driver and switching frequency. For guidance on picking sufficient gate drive strength, *Fundamentals of MOSFET and IGBT Gate Driver Circuits* would be a great resource.

The initial gate resistance can be changed until the desired drive strength is achieved. For guidance on selecting gate resistance, the *External Gate Resistor Design Guide for Gate Drivers* can be a good resource.

3.9 Considerations of the PTC Load

The PTC load is the element that heats up once current is supplied to it. The more current flowing through the PTC load, the hotter the load will get. This trend continues to a certain magnitude of current, then the resistance of the PTC load will significantly increase, limiting the current flowing through the load. In their article "How does a PTC heater work?", DBK USA explained the resistive characteristics of a PTC heater in detail. Figure 3-16 is a graph from the article mentioned above showing that trend. The heat is either captured by the coolant of the HVAC system or blown directly throughout the cabin. The power rating of the PTC load can vary from about 5Kw to well over 10kW.



A. Traction inverter: 15kW to 400kW

B. EV charger: 3.3kW to 22kW

C. PV booster and inverter: 5kW to 1MW

Figure 3-16. PTC Load Resistance Based on Temperature

When designing the control module and algorithm, it is critical the understand the resistive properties of the specific PTC load being used. A specific current magnitude flowing through the PTC load will result in a specific load temperature being achieved. So, it is highly recommended that the current, voltage and temperature that the PTC is experiencing is measured and monitored. This way, the current and voltage can be cross checked with the temperature to ensure that the PTC load is achieving the desired heat. Guidance for measuring temperature can be found in the "Selection of the temperature sensing" section. Measuring current may not be enough on its own due to possible variations in DC Bus voltage or resistive properties of the PTC load. Monitoring the current and heat can also help ensure that the PTC loads' power rating is not exceeded, avoiding damage to the module, vehicle, and user. Guidance on monitoring load current can be found in Section 3.10.

3.10 Designing the Load Current Monitoring

The load current monitoring circuit in the PTC system measures the current coming from the load so the module can react quickly to short circuit faults in order to protect the components and system as a whole.

If the designer has picked either a switch driver without integrated overcurrent protection or an MCU without integrated comparators or switch drive without a dedicated enable pin. A block diagram for a common algorithm can be seen in Figure 3-17.

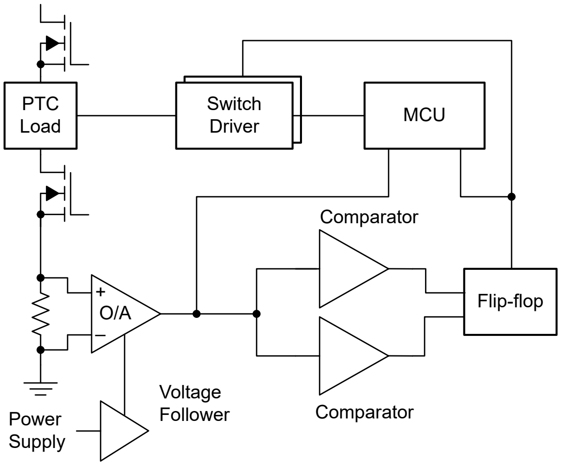


Figure 3-17. Load Current Monitoring Circuit Block Diagram

A shunt resistor is placed below the PTC load. A differential op amp measures the differential voltage across the shunt created by the load current. A good differential op amp for this kind of application may have high speed, low noise, low offset, and a bandwidth that meets the gain requirements, like the OPA607-Q1. This device has a suitable slew rate of 24V/µs, low typical quiescent current of 900µA and is low cost. A voltage follower functions as a reference voltage source for the op amp. In this case, the power supply can be used as the reference voltage. The TLV9001-Q1 can used as the voltage follower due to it having unity gain stability.

A designer can consider monitoring the op amp output with an ADC from the MCU. This can reduce cost and board-space, but, however, is not the fastest way to detect the short-circuit current and overcurrent in the PTC load. For faster detection, each differential op amp can output to two comparators, one of which is inverted. The inverted comparator enables shunt current detection in the opposite direction. When an overcurrent or short-circuit event occurs on a PTC load leg, the respective comparator detects it and changes its output state accordingly. The designer must pick a comparator whose response time allows an overcurrent or short circuit fault to be detected in the desired amount of time. Comparator power consumption relies on its speed, so a designer must take in to consideration the component's speed to power ratio to ensure it power consumption fits the requirements of the given application. To help mitigate this risk at a low cost, one could use a comparator with a good speed-to-power ratio like the LM393LV-Q1 (25uA per channel). This part has a 600ns propagation delay. If a lower speed-to-power ratio and propagation delay is needed, then the TLV9022-Q1 is a great alternative if a higher component cost can be accepted. This part offers 15uA per channel and a short propagation delay of 100ns.

The comparator outputs can be connected to the clock input of a flip-flop to latch the overcurrent signal. The preset, power supply and data inputs can all be tied high together, while the flip-flop reset signal will be from the MCU. For this application, the flip-flop needs only one data channel. A single channel flip-flop suitable part for this would be the SN74LVC2G74-Q1. An example how this can be implemented is in the "Automotive high voltage, high power motor driver reference design for HVAC compressor" TIDA-01418.

If the high-side switch driver(s) does not have an enable/disable input pin, then the flip flop latches its output and disables the octal buffer between the MCU and switch drivers. Thus, the buffer acts as a discrete enable pin. Ensure that this component has enough drive current to turn on the switch driver via its input. A buffer suitable for this application is the SN74AHC1G125-Q1. With ±8-mA of drive current, it is more than capable of operating most switch drivers. As soon as the buffer is disabled, the switch driver input signals are pulled down and make the power switches turn off.

If the high-side switch driver does have an enable/disable, then a buffer is not needed and the flip-flop output can be directly attached to that pin. If the designer selected low side switch drivers with enable pins, then the designer has a few options. They can have the flip-flop output connect to the low-side switch driver's enable pins to that both high- and low- side switch drivers are shut off in the case of an overcurrent or short-circuit fault condition. Or, if there are multiple PTC loads and respective high side switches in parallel, like Figure 2-8, the designer can have a designated GPIO pin from the MCU for each low-side switch driver. So, if there is a fault one leg, that load can be cutoff while the other legs still receive power. However, a drawback to this is that MCUs are usually too slow for fault protection purposes.

If the designer selects a gate driver to drive the switch with integrated overcurrent (OC) protection, then they have the ability to save PCB board space and possibly total system cost. The algorithm is as follows:

A shunt resistor is placed below the PTC load. The overcurrent (OC) pin measures the voltage of the shunt resistor. A shunt resistor has low impedance, compared to the PTC load itself and will have a low voltage drop and minimal power dissipation. The resistance of the load varies as well, so measuring the voltage drop for overcurrent detection would be more complicated. If the shunt voltage is higher than a predetermined threshold, then the gate driver will safely pull down the IGBT gate and shutdown softly to reduce transients. The fault pin of the switch driver will then send a fault signal to the MCU. After the fault is detected, the switch driver output is held low until a signal is sent to the reset pin of said switch driver.

Similarly, integrated desaturation protection is another method of overcurrent detection. The desaturation detection pin (DESAT) measures the collector-emitter (drain-source) of the IGBT. If this is higher than the specified desaturation threshold voltage (V_{DESAT}), then the gate driver will safely shut down the IGBT and report the fault signal to the MCU.

When a fault signal is sent to the MCU, the designer has the flexibility to either have all switch drivers shut off or just shut off the switch driver for the leg with the fault. This eliminates the need for a discrete load monitoring circuit, thus limiting the component count, reducing the size of the PCB and simplifying the design. A switch driver with integrated desaturation protection is the UCC57108-Q1, a low-side gate driver that also has 4-amp drive strength. A drawback to this approach is that it might not save cost since a switch driver IC with integrated DESAT protection may be more expensive than a switch driver without DESAT protection paired with a discrete load current monitoring circuit.

3.11 Selection of the Temperature Sensing

Temperature sensors measure the heat from either the power switches or the PTC load and feed the information back to the MCU within a specified accuracy.

When picking a temperature sensor, the first factor a designer may want to look for is accuracy. A temperature accuracy within 2°C-3°C may be sufficient for PTC load and power switch temperature. An attribute that greatly impacts accuracy is the device's power consumption. The device's "self-heating" can negatively impact the measurement read and fed back to the MCU. The TMP235-Q1 has a maximum temperature accuracy of ±2.5°C, so it provides a great balance of cost and accuracy.

Another factor to consider is the package size of the sensor. The smaller the package, the faster the response time. If your system requires a fast response time, in conditions such as rapid overheating of the power switches, the PTC load suddenly going past its power rating and so forth, consider the package size of the temp sensor. Regarding fast power switches temp response, you can use a device like the ISOTMP35-Q1. This is an isolated temp sensor that lets you connect to the HV power switches for instant response.

If the goal of the application is to achieve the lowest cost PTC module possible, a designer can use a negative temperature coefficient (NTC) sensor. However, if the designer wants more accurate temperature measurements without having to use a linearization circuit, as well as less resistance tolerance variation than what traditional NTCs can provide, a PTC thermistor like the TMP61-Q1 can be a good choice. This sensor also comes with a fast response time of 0.6s, enabling the PTC heater control module to respond to overtemperature conditions quickly.

Placement is one of the most important factors when implementing this component in your PTC heater module. Proper placement is critical for accurate readings. Air is by far the worst medium for measuring temperature, so place the temperature sensor as close to the power switch or PTC load as possible to provide proper ambient temperature sufficient measurement. One can measure hotspots of the power switches to help maximize the performance without getting overheated. However, capturing this usually requires more expensive temperature sensors.

4 Summary

The electrification of vehicles has driven automakers to take on new challenges, such as how to design thermal management systems for the best result to the user while saving of cost and weight of the end vehicle. The different solutions available in the market today have their own advantages and tradeoffs, so it is up to the discretion of the designer on which solution to choose from. Though PTC's are not the most efficient system for heating, they offer significant benefits in cost, weight, and design simplicity.

For more resources on automotive heating and cooling, please visit the Thermal management applications page and read the *How to design heating and cooling systems for HEV/EVs*.

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