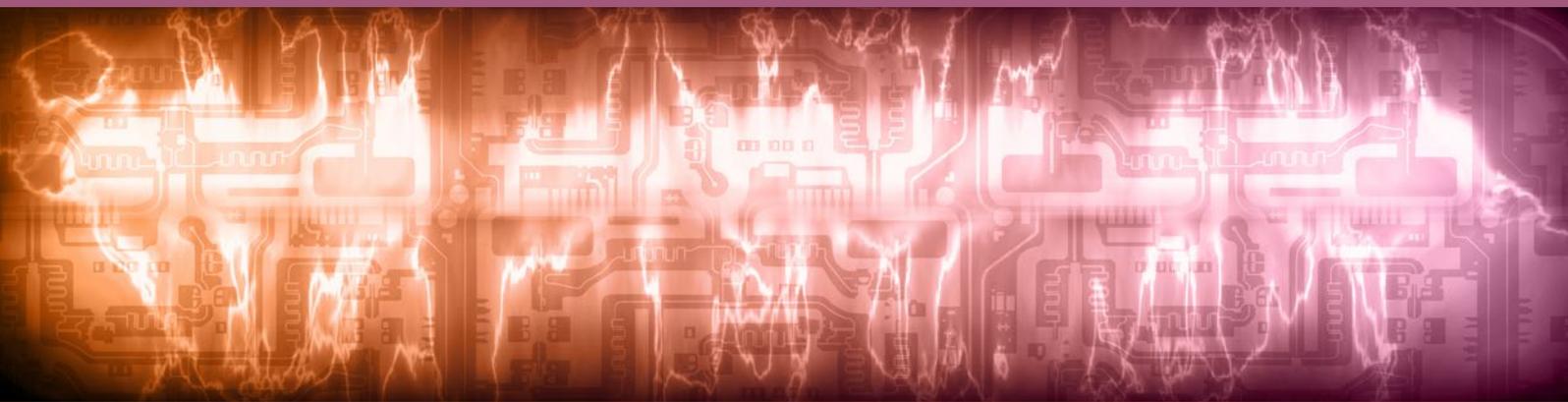# Selecting the Optimal Inductor for Power Converter Applications

SDR Series Power Inductors
SMD Non-shielded

SRN Series Power Inductors
SMD Semi-shielded

SRP Series Power Inductors
SMD High Current, Shielded

SRR Series Power Inductors
SMD Shielded

SRU Series Power Inductors
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Toroid Inductors

BACKGROUND

Today's electronic devices have become increasingly power hungry and are operating at higher switching frequencies, starving for speed and shrinking in size as never before. Inductors are a fundamental element in the voltage regulator topology, and virtually every circuit that regulates power in automobiles, industrial and consumer electronics, and DC-DC converters requires an inductor. Conventional inductor technology has been falling behind in meeting the high performance demand of these advanced electronic devices. As a result, Bourns has developed several inductor models with rated DC current up to 60 A to meet the challenges of the market.

Especially given the myriad of choices for inductors currently available, properly selecting an inductor for a power converter is not always a simple task for designers of next-generation applications. Beginning with the basic physics behind inductor operations, a designer must determine the ideal inductor based on radiation, current rating, core material, core loss, temperature, and saturation current. This white paper will outline these considerations and provide examples that illustrate the role each of these factors plays in choosing the best inductor for a circuit. The paper also will describe the options available for various applications with special emphasis on new cutting edge inductor product trends from Bourns that offer advantages in performance, size, and ease of design modification.

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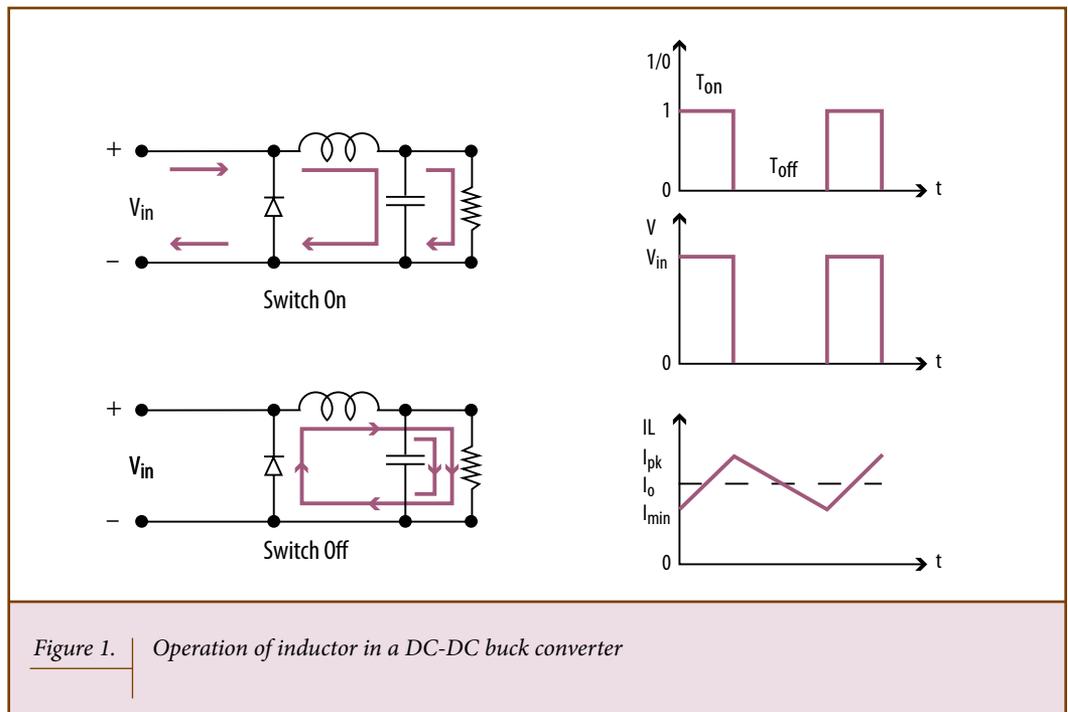SMD Shielded

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Back to Basics

A brief tour of college physics explains all that is necessary to understand the basic operation of an inductor, which can be described simply as a component that stores energy in the form of magnetic flux. Faraday's Law of Induction states that change in magnetic flux induces electromotive force which opposes the driving current. This relationship describes the inductor:

$$e = -N \, d\varphi/dt = -L \, dI/dt$$

Current through an inductor is transformed to produce a magnetic field. It charges and current rises when the circuit is on. When off, the inductor acts as a current source, discharging current that flows through the circuit as the magnetic flux collapses.

Figure 1. | *Operation of inductor in a DC-DC buck converter*

In continuous current mode, the inductor current does not fully discharge to zero during the portions of the cycle in which it is off. A voltage change across the inductor is instantaneous while the current through an inductor varies with time.
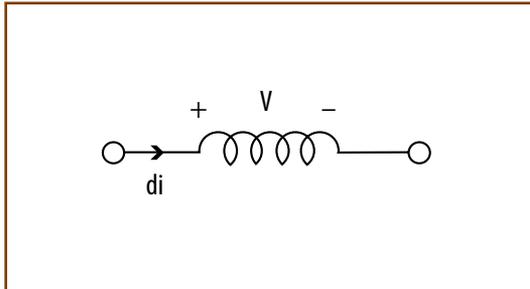
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Back to Basics *(continued)*

Figure 2. | *Voltage across an inductor*

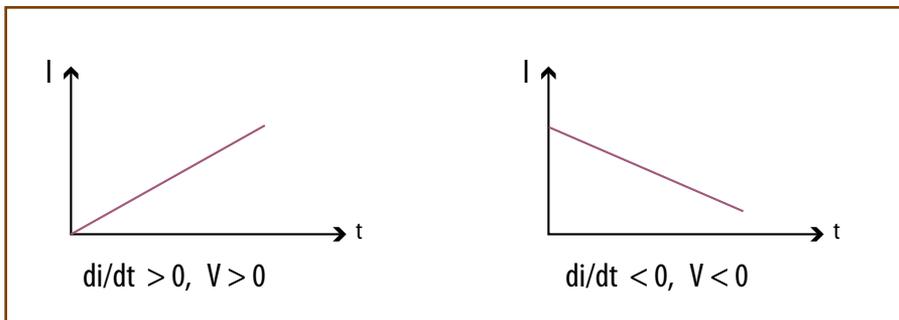The voltage and current components of the inductor are out of phase such that the voltage leads by 90 ˚.

di/dt > 0, V > 0   di/dt < 0, V < 0

Figure 3. | *Inductor current over time*

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Selecting the Shielding Environment

One of the first design considerations before selecting an inductor is its placement on the board and the sensitivity of components that will be in its immediate vicinity. From this either a shielded or non-shielded configuration can be chosen, each of which has distinct advantages and disadvantages. The main advantage of a shielded inductor is its low radiation which can be characterized from its lowest coupling factor among other type of inductors, whereas the magnetic flux of its non-shielded counterpart is not confined to a given vicinity. These inductors experience the highest coupling factor. Bourns introduced the semi-shielded inductor series using magnetic epoxy resin as a magnetic shield in 2011. As its name suggests, the semi-shielded inductor is design to bridge the performance gap of shielded and non-shielded inductors by offering users an additional selection of inductor series.

Table 1.	Non-Shielded / Semi-Shielded / Shielded / High Current-Shielded Inductor Coupling Factor - K			
Inductor	**SDR0805** 10 µH 8 x 8 x 5 mm	**SRN8040** 10 µH 8 x 8 x 4 mm	**SRU8043** 10 µH 8 x 8 x 4 mm	**SRP6540** 10 µH 7 x 7 x 4 mm
	Non-shielded	**Semi-shielded**	**Shielded**	**High Current-Shielded**
Series				
Coupling Factor - K*	22.8 %	16.6 %	0.37 %	0.27 %

Coupling factors of non-shielded / semi-shielded / shielded / high current-shielded inductors in similar sizes are compared at a 100 kHz test frequency with a pair of DUT placed next to each other.
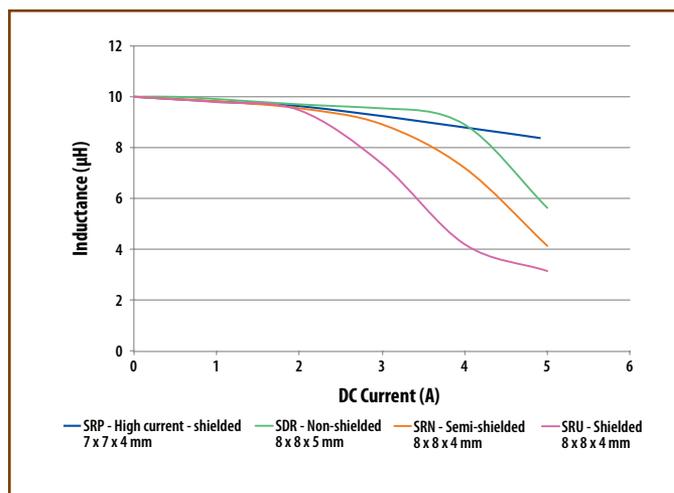
Figure 4. Non-Shielded / Semi-Shielded / Shielded / High Current-Shielded Inductor DC Current Saturation Characteristics

Larger size, a faster inductance roll-down, greater cost, and a lower saturation current are the downfalls of the shielded inductor. Non-shielded components are smaller, rated for higher saturation current, and cost less, though these advantages may be of no importance if the radiation environment is a key requirement in a design. Semi-shielded inductors combine some of the features of non-shielded and shielded inductors where the saturation current chacteristic falls in between the other two types of inductors. They are a lower cost alternative of the shielded series.

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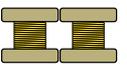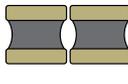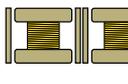SRN Series Power Inductors
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Selecting the Shielding Environment *(Continued)*

Another option which is growing in popularity due to its unique design features is the toroid inductor. The toroid shape results in an inductor which performs like a shielded component. Distributed air gap construction provides high current handling capacity.

Figure 5. | *Self-shielding of toroid inductor*
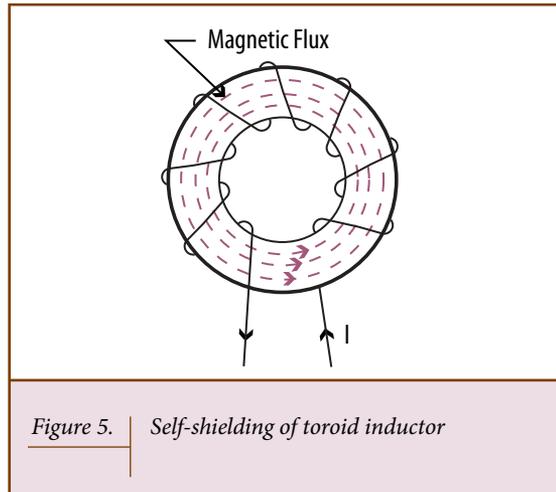
Inductor Rated Currents

When current flows through an inductor the temperature of the component rises, AC ripple current causes core loss, and DC current causes inductance to drop. The amount of steady state DC current, referred to as I_{rms}, which causes the temperature to rise is typically in the 20-40 ˚C range and effectively provides a benchmark of power dissipation for the component. Another way to classify I_{rms} is the output or average current of a switching regulator.

Figure 6. | *I_{rms} vs time*

I_{rms} is referenced only when AC ripple current is low and core loss is negligible.

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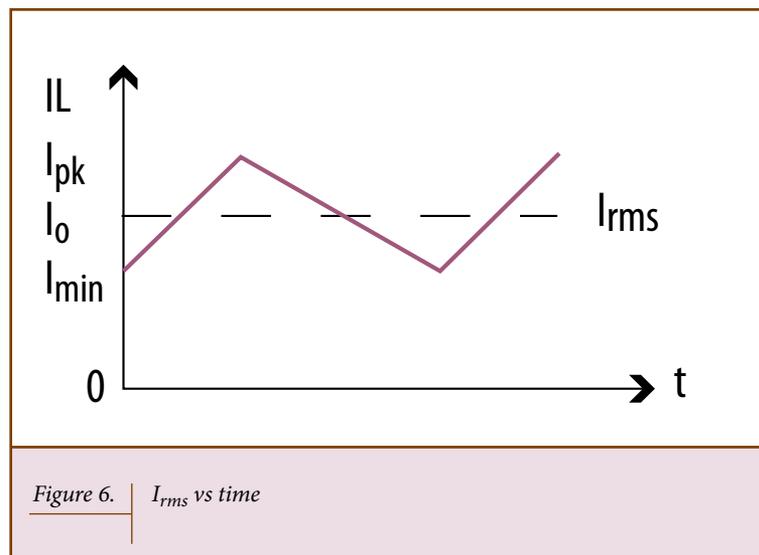J.W. Miller® Through-Hole
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Core Material and Loss

Core loss is related to the material chosen and the core cross sectional area as well as the ripple current, switching frequency, and inductance associated with the circuit. An inductor dissipates power both in the material of the core and in the windings. Core loss is calculated by taking the difference between the energy that goes into the core during the on portion of the cycle and the energy that goes out of the core during the off cycle. The following table provides data on the core loss and related cost of four different core types.

Table 1.	Core loss and cost by material type	
Material	**Core Loss @ 250 KHz, 100 g (mw/cm³)**	**Related Cost**
Ferrite (gapped)	1	Low
Iron (75 µ)	80	Low
Sendust (60 µ)	35	Medium
MPP (60 µ)	8	High
Ferrite = Mn-Zi	Sendust = Fe-Al-Si	MPP = Me-Ni-Fe

Power dissipation is given as the sum of the I_{rms} current power calculated from the classic equation $P = I^2 R$ and the AC ripple current for core loss.

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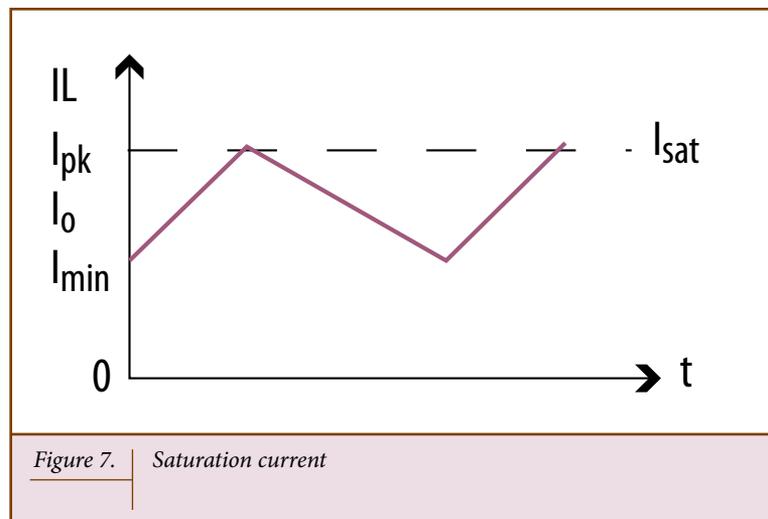SMD Shielded

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Temperature and Saturation

When examining the temperature range for the inductor, a designer should be aware that the operating temperature and the ambient temperature are not one and the same, but rather the operating temperature is the difference of the ambient temperature and self-rising temperature. For example, a given component with an operating temperature in the range of -40 to +125 ˚C with a self-rise temperature of +40 ˚C means the ambient temperature is actually -40 to +85 ˚C where the difference is taken only on the maximal temperature. Since the operating temperature cutoff is -40 ˚C, the range is not able to extend beneath that value. Furthermore, temperature is a function of power dissipation and surface area given by the equation:

$$\Delta T = f(power\ dissipation) / f(surface\ area)$$

Saturation current, denoted as I_{sat}, is defined as the amount of DC current to cause inductance drop. This is typically 5-35 % of its initial value. I_{sat} is a benchmark of current handling capability for an inductor, characterizing the amount of energy that can be stored based on the relationship of energy that is stored in the inductor, which is ½ LI^2 and essentially infinite. The term saturation current does not imply that the inductor core has reached the saturation stage, rather the component is at the magnetized stage. I_{sat} can be considered as the peak current of a switching regulator to account for worst case saturation. Since a high saturation current does not drive the component to zero inductance, it becomes an air inductor remaining above zero. If the current goes high enough during operation then the core material and wire insulation can be damaged at high temperature. In most cases, the operation of an inductor is limited by its temperature rise.

Figure 7. | *Saturation current*

Example of Selection and Core Loss

Given the inductor basics, in the following example we will walk through the process of selecting an inductor for a buck converter, a circuit that is frequently used to step a voltage supply down to a lower regulated voltage. A buck converter is able to provide a stable and efficient output voltage when designed correctly.

Figure 8. | *DC-DC buck converter*

The specifications of the circuit are:

$$V_{in} = 8 \text{ - } 12 \text{ } V; \text{ } V_o = 5 \text{ } V; \text{ } I_o = 0.5 – 2 \text{ } A; \text{ } f_{switch} = 250 \text{ } kHz$$

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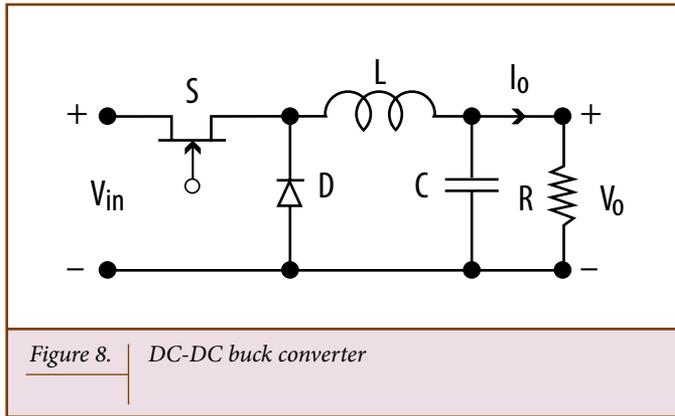
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Example of Selection and Core Loss *(continued)*

It is known that the circuit is in continuous current mode such that it does not discharge fully to zero during the off cycle. With this information it is possible to determine the specifics of the inductor for the buck converter.

1. Calculate the total time period, $T = 1 / f$

$$T = 1 / 250 \ kHz = 4 \ \mu s$$

2. The minimum duty cycle can be calculated from $D_{min} = V_o / V_{in}(max)$.

$$D_{min} = 5 \ V / 12 \ V = 0.4 \ for \ V_o = 5 \ V \ and \ V_{in}(max) = 12 \ V$$

3. The on time can be calculated as $T_{on} = T \ x \ D_{min}$

$$T_{on} = 4 \ \mu s \ x \ 0.4 = 1.6 \ \mu s$$

4. Inductor ripple current, which typically is no more than 30 % of the maximal output current, is the fourth variable to calculate: $dI = I_o(max) \ x \ 0.3$

$$dI = 2 \ A \ x \ 0.3 = 0.6 \ A$$

5. Voltage across the inductor is given by $V = V_{in}(max) - V_{out} - V_{diode}$

$$V = 12 \ V - 5 \ V - 1 \ V = 6 \ V$$

6. Minimal inductance is calculated by manipulation of the inductor equation: $V = L \ dI/dt$

$$L_{min} = V \ dt/Di = 6 \ V \ x \ 1.6 \ \mu s \ x \ 10\text{-}6 \ s \ / \ 0.6 \ A = 16 \ \mu H$$

7. Now the inductance can be selected based on the criteria of a 20 % tolerance. It is dropped 10-35 % at the rated current as well

$$L = 16 \ \mu H \ / \ (0.8 \ x \ 0.65) = 31 \ \mu H$$

Shifting this value higher to 33 μH provides the minimum for continuous mode operation.

8. The peak current is given by $I_{peak} = I_o(max) + dI/2$

$$I_{peak} = 2 \ A + 0.6A \ / \ 2 = 2.3 \ A$$

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Example of Selection and Core Loss *(continued)*

For the same inductor the core loss can be calculated and analyzed.

1. Additional information for this calculation is the number of turns, N = 20, and the cross sectional area of the core A = 0.071 cm^2. Magnetic flux is defined as $B_m = (dI \times L \times 108) / (2 \times N \times A)$

$$B_m = (0.6\ A \times 33\ \mu H \times 108) / (2 \times 20 \times 0.071\ cm^2) = 700\ Gauss$$

2. Given a core loss per unit volume of 150 mW/cm^3 and a core volume V_e = 0.2 cm^3, the core loss can be calculated

$$150\ mW\ /\ cm^3 \times 0.2\ cm^3 = 30\ mW$$

3. DC loss is given by the power equation P = I^{2}R

$$P = (2\ A)^2 \times 0.06\ ohms = 240\ mW$$

This core loss is less significant for temperature rise, and the DC loss is high in comparison. Most of the loss in this case will be from the copper wire.

Choosing the Optimal Inductor

Now that all the information for the part has been calculated, a search through the product catalog will enable proper component selection. Bourns offers a vast range of components with inductance values of 0.1 µH to 15 mH, current ratings from 60 mA – 43 A$_{rms}$, and saturation currents up to 65 A. Choosing the right part is straightforward when the following sequence is employed:

1. Choose the configuration that corresponds to the design's current based on the maximal output current.
2. Find the components which have the necessary inductance.
3. Choose the desired DC resistance.
4. Narrow the choices to the type of construction or coil type desired.
5. Select the specific part number.
6. If necessary, use a cross reference table to convert to the latest Bourns® component.

This process is applicable when choosing an inductor for any application from the broad line of inductor product families offered by Bourns.

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Bourns New Product Trends

Bourns has been in the business of inductors and magnetics for more than four decades and is committed to offering cutting edge components as the electronics market evolves. Applications such as cellular phones, mobile devices, laptop computers, industrial electronics, and entertainment electronics are creating new demands on inductors in terms of size, performance, and radiation.

Bourns® SDR family of surface mount power inductors are non-shielded and range in inductance from 0.68 µH to 15 mH. The output current capacity of this family of inductors is 0.06 to 16 A. A variety of package shapes and sizes are available including round, oval, and square offered with a profile as low as 2.2 mm.

Bourns® SRN family of surface mount power inductors are semi-shielded inductors utilize magnetic epoxy resin as a shield which provides effective magnetic shielding while emitting lower radiation compared to non-shielded inductors. In addition, the models offer a reduced footprint and cost savings to comparably-sized shielded inductors. The series have inductance values from 0.5 to 470 µH. The output current capacity of this family of inductors is up to 10 A. Profiles as low as 1 mm are offered.

SRR series inductors are shielded surface mount components offered in round or square packages ranging in inductance from 0.47 to 15,000 µH. The output current capacity of this family of inductors is 0.07 to 20 A. These surface mount power inductors are ideal for car stereos, CD players, camcorders, LCD displays, portable communication devices, and at the input and output of DC-DC converters. These components are RoHS compliant for the continual trend in environmentally friendly design and manufacturing.

Given the new product trends, Bourns also offers SRU models which have shielded construction for low radiation. This family of inductors remains compact in size (profiles as low as 0.9 mm) with a near round shape to facilitate efficient board footprints. Unique to this family of SRU inductors is that four or more parts are made with the same footprint. If a variable in part selection, the part profile, or some combination of these elements needs to be changed then it is simple for the part to be replaced without impacting the board's mechanical design or forcing a board respin. Remaining ahead of the curve in the manufacturing realm, Bourns® SRU packages feature an octagonal body to eliminate part rotation in a tape carrier and ensure proper orientation when placed on the board. High powered shielded inductors are gaining popularity in many applications.

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Bourns New Product Trends *(continued)*

Another feature of Bourns® SRP inductors is the adoption of flat wire instead of round wire. This is especially beneficial in high frequency applications up to 5 MHz. Some advantages of using flat wire within the component include a compact package, optimizing the space utilization afforded by stackability. A flat wire allows 95 % of the area to be used, a marked improvement over the 70 % utilization of a package containing round wire. While having a more compact package, there also is more surface area to reduce AC resistance. Especially at high frequencies, the skin effect dictates that the current will travel on the surface. Contrasting a round and a flat conductor with the same cross sectional area of 0.64 mm^2, the unit surface area of 4.64 mm^2 for the flat conductor is nearly double the 2.83 mm^2 provided by the round wire. The molded core construction of the device provides additional benefit since the package space is fully utilized to allow maximum performance with the core material molded to the winding. The space inside the package is filled with the magnetic compound and provides high inductance, shielded construction as well as high current handling capacity.

Bourns is preparing to introduce more than two dozen additional SMD power inductor families in multiple phases, especially designed for automotive applications. These inductors will utilize non-shielded and shielded construction and are AEC-Q200 qualified.

Custom Power Inductor Solutions from Bourns

To complement Bourns' four decades of inductor expertise along with the company's existing competencies in this market, Bourns acquired the entire magnetics line of J.W. Miller, a company with 70 years of leadership in inductor technology. A key capability of Bourns is the expertise to provide a custom solution in as little as six to eight weeks. Bourns regularly works with designers to adjust manufacturing parameters such as the core type and number of turns to deliver a custom component that will meet requirements. The world-class experts at Bourns are available to team with designers in the development of custom solutions to meet package current, inductance, and size requirements.

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Conclusion

In this consumer-driven market it is expected that portable electronics will continue to shrink to meet user expectations and demand. In order to maintain their competitive edge, designers are able to start with the most fundamental building blocks of design such as highly reliable and compact inductors. With a grasp on the basic physics of inductors and an example to follow, the guesswork previously associated with selecting a power inductor has been removed. Following the guidelines set forth in this white paper the appropriate Bourns® inductor, whether custom or standard, can be incorporated into a design to ensure ultimate reliability in the most demanding applications. The compact size, modification flexibility offered by a standard footprint, and long proven track record in the industry ensures that designers will find the optimal inductor solution from Bourns® broad line of products.

For more information on inductors and other products from Bourns, please visit

www.bourns.com

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Asia-Pacific: *Tel* +886-2 256 241 17
Fax +886-2 256 241 16