Keywords: switching regulators, DC-DC converters, electric bikes, e-bikes, power conversion, power subsystem, power design, power systems

APPLICATION NOTE 6559

DESIGNING EFFICIENT POWER SYSTEMS FOR E-BIKES

Abstract: Electric bicycles (e-bikes), especially those with lithium-ion (Li-ion) batteries, are becoming increasingly popular around the world. Statista projects that worldwide sales of e-bikes will grow to 40.3 million units by 2023[1]*. This application note discusses why it's important to pay close attention to overall power conversion efficiency and total solution size when designing power systems for e-bike controllers. It also covers ways to implement small, efficient power subsystems for e-bikes.*

Introduction

China currently has the largest share of the e-bike market; however, most of these bikes are based on older sealed lead acid (SLA) battery technology. There are two important market trends in the China e-bike market to note:

- The market is experiencing a transition from SLA batteries to new and lighter Li-ion battery chemistry, which does call for more complex electronics
- To increase the riding range of e-bikes, we are seeing higher battery capacity driving higher voltages (up to 54V nominal)

Transitioning to a higher voltage Li-ion chemistry involves developing a small, light control unit that can deliver enough range to make the bike viable in an urban environment. This involves significant system design challenges, especially when it comes to the power subsystem.

What Do E-Bike Controllers Need?

Figure 1 shows a generic system block diagram of an e-bike controller.

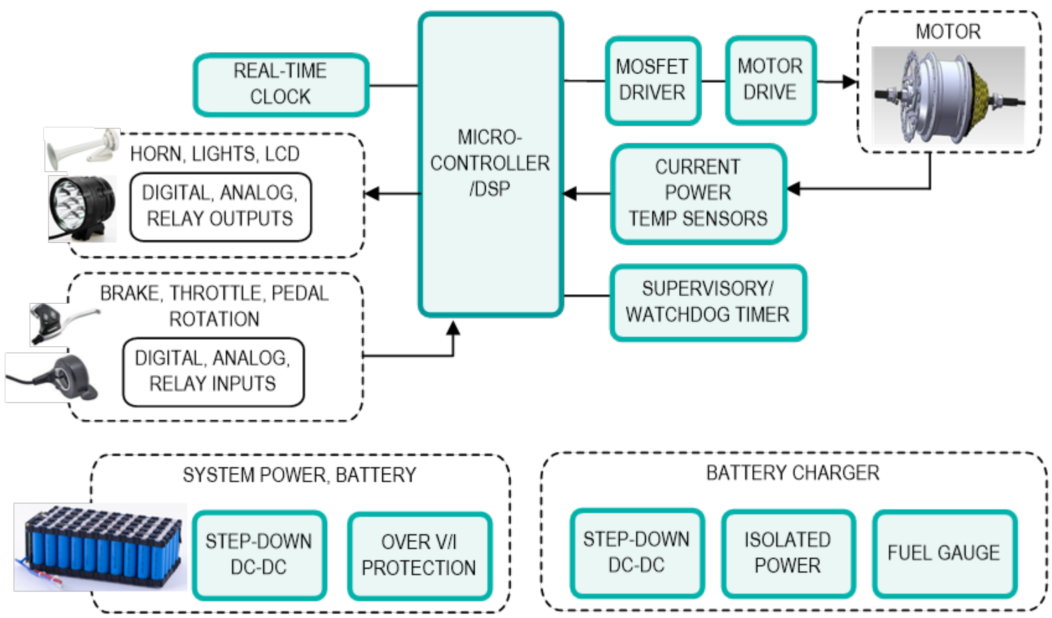


Figure 1. Generic system block diagram of e-bike electronics.

A Li-ion battery, 36V and up (depending on the number of battery cells used), provides the power for the system. This battery powers the motor, the MOSFET drivers, and the microcontroller as well as other ancillary functions like the horn, lights, and hall-effect sensor in the main motor (mostly a brushless DC motor). In **Figure 2**, you can see a generic power architecture.

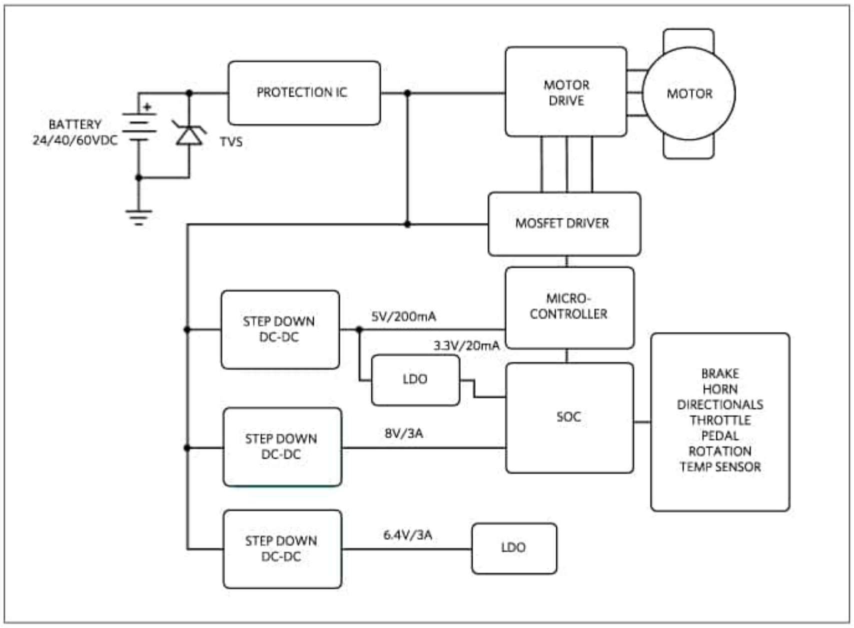


Figure 2. A generic e-bike power architecture.

While existing e-bike controllers are large and bulky, their new counterparts are designed to fit within the frame and/or under the seat of the e-bike. This placement means that the Li-ion battery controller must have a very small solution size and also very low heat generation, which is now being dissipated in a much smaller area.

How Power Solution Efficiency Affects E-Bike Range

The battery pack size and the power conversion efficiency of the power subsystem used affect an e-bike's range. Say you've got an e-bike with a 36V/10Ah battery pack. The energy in the battery pack is 36V × 10Ah = 360Wh (Watt.Hour). The discharge rate, ambient temperature, and other factors affect the usable energy in the battery. For simplicity, let's assume all this energy is available to drive the bike. Now, assume the energy used per mile is 14.4Wh (a very typical number for e-bikes). As the power system efficiency goes up, here's what happens:

At 80% efficiency:

Power used to drive the motor	= 360Wh × 80% = 288Wh
Range of this e-bike	= 288Wh/(14.4Wh/mi) = 20 miles
Power dissipated as heat	= 360Wh - 288Wh = 72Wh (or 259kJoules)

At 90% efficiency:

Power used to drive the motor	= 360Wh × 90% = 324Wh
Range of this e-bike	= 324Wh/(14.4Wh/mi) = 22.5 miles
Power dissipated as heat	= 360Wh - 324Wh = 36Wh (or 130kJoules)

Moving power system efficiency from 80% to 90% can give you a 12.5% increase in range and 50% reduction in heat generation that must be dissipated. The Li-ion battery and electronics lifecycle both degrade with temperature—a critical decision to make.

Table 1 summarizes the range and heat generated with different power conversion efficiencies.

Table 1. Range and Heat Generated at Different Efficiencies

	Efficiency at 80%	Efficiency at 90%
Range	20 miles	22.5 miles
Heat Generated	72Wh (259kJ)	36Wh (130kJ)

Now, let's take a look at some of the latest synchronous DC-DC converters in the market, and see how their specifications can enable an optimum power subsystem for an e-bike controller.

Power Design Examples

Here are a few power design examples using a couple of popular ICs in the market today.

Design requirement:

V_{IN} range: 27V DC to 42V DC
V_{OUT}: 5V at 2A
T_{AMB}: +30°C

Let's start with Maxim's MAX17503, a 4.5V to 60V, 2.5A, high-efficiency, synchronous step-down DC-DC converter. Using the EE-Sim® DC-DC Converter tool and choosing a *balance design* between efficiency and size, the complete power system looks as shown in **Figure 3a** and **Figure 3b**.

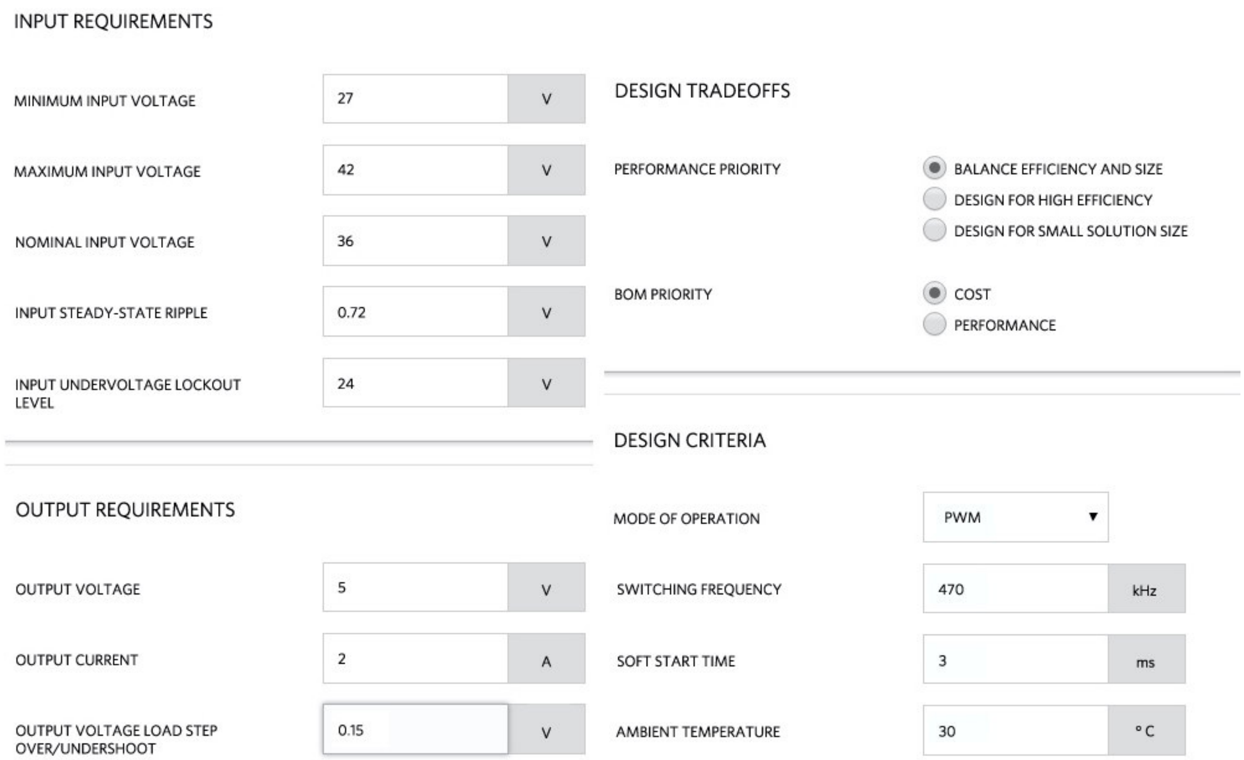


Figure 3a and 3b. Complete power system readings from EE-Sim DC-DC Converter tool.

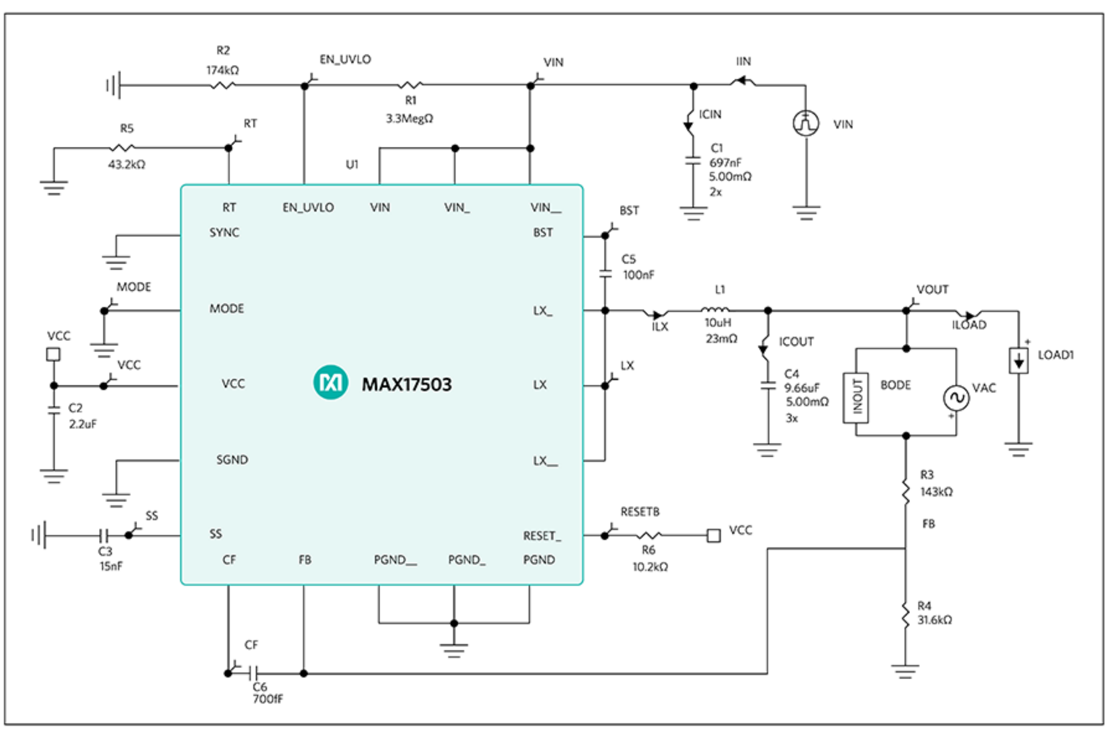


Figure 3c. MAX17503 block diagram.

This power solution, which features a relatively small inductor (10mH), delivers an 86.5% power conversion efficiency—V_{IN} = 36V, V_{OUT} = 5V at 2A running at 470kHz switching frequency. Its total solution footprint is 156mm , as shown in **Table 2**. The external inductor specifications and the small package of the IC itself contribute to the ultra-small solution size. **Figure 4** features an efficiency plot for the IC.

Figure 4. Efficiency plot for MAX17503.

Table 2. MAX17503 Balance Design Component Footprint

Component	Size (mm^2)
Input, Output Caps	26
Output Inductor	108
IC	16
Others	6
Total	156

In older e-bikes sold in China, a 3.5V to 60V input, 2.5A step-down converter has been used. We can call this converter Device T. Using Device T's online simulation and sizing software, we can estimate size and efficiency of the power system designed with this component (**Figure 5a**). For our examination, we selected three design options: one seeking a balance between efficiency and size, the second optimized for size, and the third focused on achieving the highest efficiency.

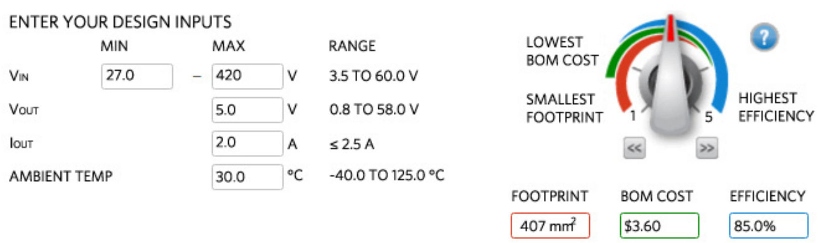


Figure 5a. Simulation tool for Device T.

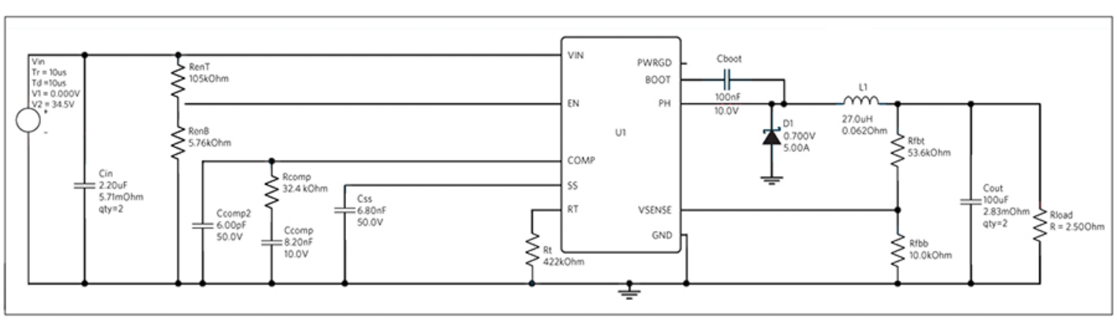


Figure 5b. Sample Device T.

This balanced design runs at 295kHz, yields 85% efficiency, and has a footprint of 407mm^2. **This is more than 2.5x the size of the MAX17503 design with a 1.5% lower power conversion efficiency.** Also, because this Device T design runs at lower switching frequency, it requires a larger inductor. The nonsynchronous rectification diode also takes up some additional space.

Let's redesign this circuit, optimizing for size as shown in **Figure 6**.

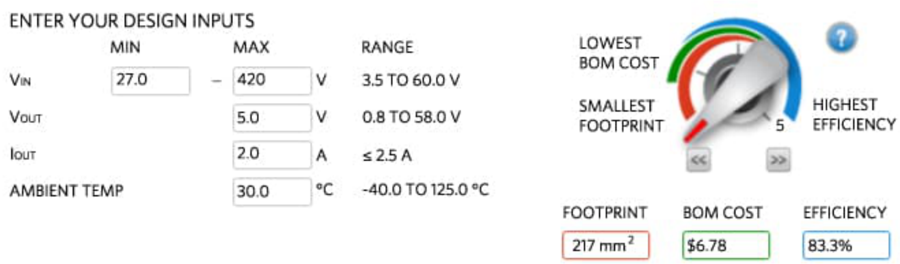


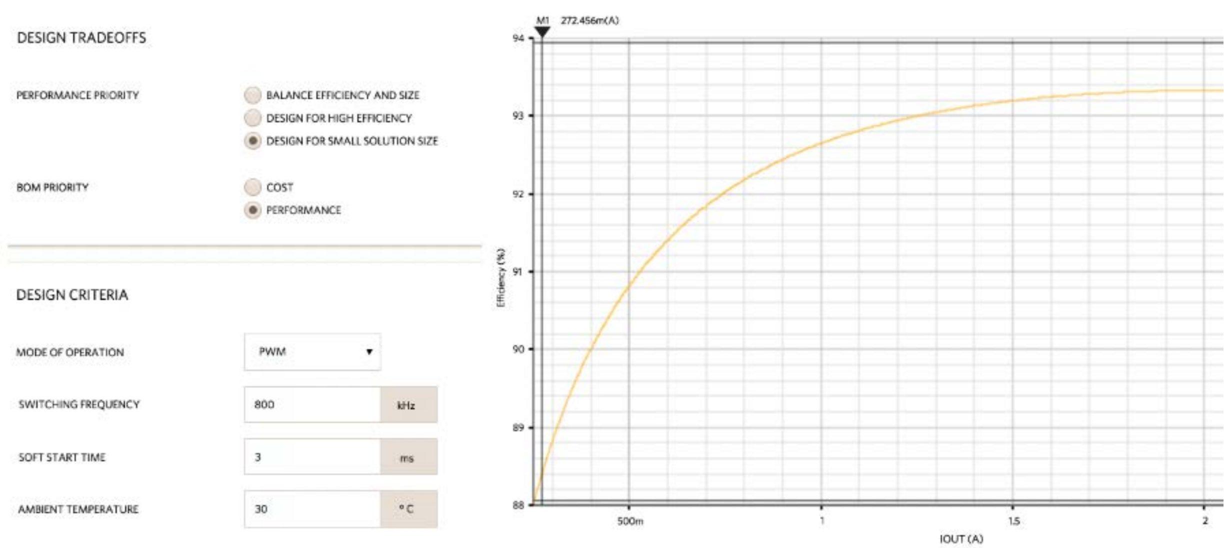
Figure 6. Redesigned circuit, optimized for size.

In this compact design, the circuit runs at 489kHz and has a footprint of 217mm^2 with even further degradation of efficiency (83.3%).

When we redo the design and optimize it for the highest efficiency, this approach yields 89%, the converter runs at 100kHz, and it has a total component footprint of 1315mm^2.

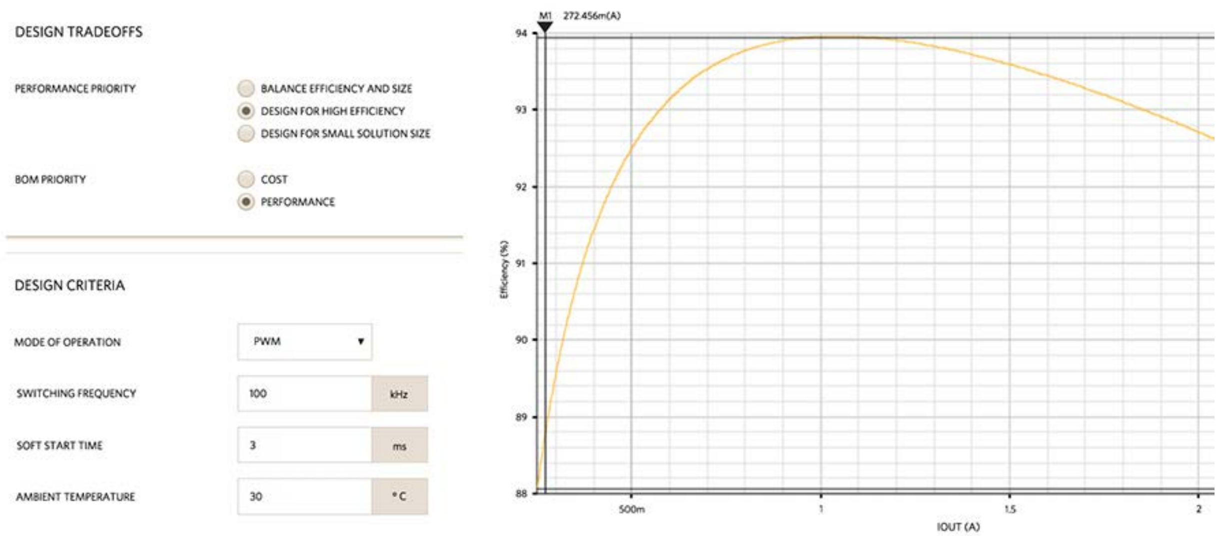
For comparison purposes, let's create two more designs with the MAX17503: one optimized for small size and another for high efficiency.

Figure 7a and **Figure 7b** show the MAX17503 optimized for small solution size.



Figures 7a and 7b. MAX17503 optimized for small solution size.

Figure 8a and **Figure 8b** show the MAX17503 optimized for highest efficiency.

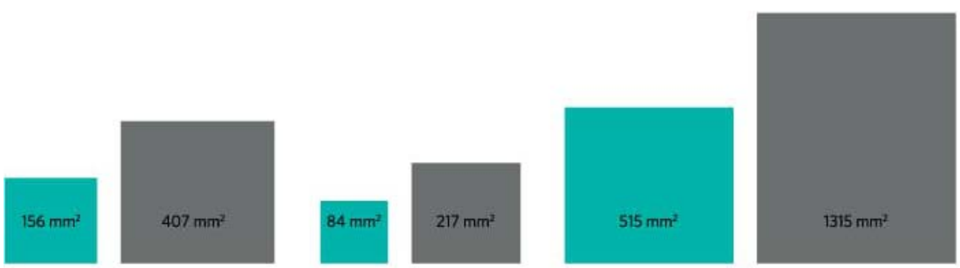


Figures 8a and 8b. MAX17503 optimized for efficiency.

Below is the summary of the design in three distinctive design optimizations for V_{IN} = 27V DC to 42V DC, V_O = 5V at 2A, T_A = +30°C.

Table 3. Comparison of Power Designs

Efficiency and Size	MAX17503	Device T	MAX17503 Differences
Switching Frequency	470kHz	295kHz	**60%** higher
Efficiency	86.5%	85%	**1.5%** more
Total Component Footprint	156mm^2	407mm^2	**60%** smaller
Power Dissipation	1.35W	1.5W	**10%** less
Smallest Size	**MAX17503**	**Device T**	**MAX17503 Differences**
Switching Frequency	800kHz	489kHz	**64%** higher
Efficiency	81.8%	83.3%	**1.5%** less
Total Component Footprint	84mm^2	217mm^2	**61%** smaller
Power Dissipation	1.82W	1.67W	**9%** more
Highest Efficiency	**MAX17503**	**Device T**	**MAX17503 Differences**
Switching Frequency	100kHz	100kHz	—
Efficiency	92.7%	89%	**3.7%** more
Total Component Footprint	515mm^2	1315mm^2	**61%** smaller
Power Dissipation	0.73W	1.1W	**34%** less



An e-bike's range is directly affected by power conversion efficiency. Even a difference of a few percentage points is crucial. In addition, because this power subsystem needs to fit in a small space (in the tubing or under the seat), the power/heat dissipation must be minimized to avoid overheating and impact on long-term reliability.

Impact of Quiescent Current and Shutdown Current

When an e-bike is used in an urban setting, there will likely be a lot of idle time. Related to this, there has been some confusion on how much a power conversion IC's quiescent current affects the driving range. Running the numbers, we find that, even when assuming an excessive amount of idle time, the percentage of the battery power that can attributed to the quiescent current of the power IC is virtually negligible.

First, let's understand how IC manufacturers specify no-load quiescent current:

- Device T specifies it as "Operating nonswitching supply current" at 138uA typical
- MAX17503 specifies it as "Input Quiescent Current in PFM mode, I_{Q_PFM}" at a comparable value of 162uA typical

Now, let's take our same bike with the 360Wh battery (20-mile range) down Wangfujing Street in Beijing, where there is one intersection at approximately every 0.2 miles. Assume that we will hit one stop for every two intersections, and that the average wait time is two minutes. During the 20-mile ride, we'd stop 50 times and total idle time would be 100 minutes. Using the MAX17503 I_{Q_PFM} of 160uA, the energy consumed during the idle time is merely 0.01Wh, or 0.003% of the total battery energy.

If we took the bike down another street where there are twice as many intersections, we'd consume 0.006% of the total battery energy for the same 20-mile trip. This is still an insignificant amount.

Regarding total shutdown current, the MAX17503 I_{IN_SH} is 4.5uA maximum while Device T's "shutdown supply current" is at a comparable value of 4uA maximum. At 4.5uA shutdown current, the MAX17503 will dissipate 0.12Wh, or 0.032%, of the total battery energy after one month in storage. Again, this is not a significant amount. Customers generally face more problems due related to heat dissipation and size.

Conclusion

When designing a power system for an e-bike controller, it's important to pay close attention to the overall power conversion efficiency and the size of the total solution, including the recommended sizes of the passive components like the inductors and capacitors. These choices have a direct impact on the range of an e-bike and the size of its system controller box.

References

[1] https://www.statista.com/statistics/255653/worldwide-sales-of-electric-bicycles/

A similar version of this application note appeared on EFY on October 26, 2017.

EE-Sim is a registered trademark of Maxim Integrated Products, Inc.

Related Parts		
MAX17503	4.5V-60V, 2.5A, High-Efficiency, Synchronous Step-Down DC-DC Converter with Internal Compensation	Free Samples

More Information
For Technical Support: https://www.maximintegrated.com/en/support
For Samples: https://www.maximintegrated.com/en/samples
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