SAE J1634 Measurements and Optimizing for Validation, and Testing EV MPG Range

Accelerate the design, validation and testing of motors and drives

SAE J1634 Measurements and Optimizing for EV MPG Range

Government agencies that define the standardization of energy efficiency metrics continue to be a manufacturers force behind the development of the next generation electric vehicle powertrains. These metrics require manufacturers to have high confidence in their measurements and motivate the optimization of efficiency. The use of purpose-built instruments for the development of electric powertrains ensures compliance with these standards and enables further optimization beyond regulation.

Regulation Demands Precision

The Environmental Protection Agency follows SAE J1634 "Battery Electric Vehicle Energy Consumption and Range Test Procedure" as the testing criteria for determining vehicle energy consumption and range testing of electric vehicles (MPG equivalency). SAE J1711 is a similar standard for plug-in hybrid electric vehicles. Table 1 provides examples of electrical energy measurements in SAE J1634.

Measurement	Units
Battery Ampere-Hour Capacity	DC Amp Hours
Discharge Energy	DC Watt Hours
DC Discharge Amp-Hours	DC Amp Hours
Power Outlet Voltage	AC Volts (RMS)
AC Recharge Energy	AC Watt Hours
DC Recharge Amp-Hours	DC Amp Hours

Table 1 – Electrical measurements made for EV MPG equivalency by US EPA

SAE J1634 makes the following requirements on electrical energy measurements:

- Total accuracy of (DC) current and voltage measurements shall be within 1% of the reading or 0.3% of full scale
- AC Watt-hour meter shall have a total accuracy of voltage and current of 1.0% of the reading or 0.3% of full scale
- Wideband instruments are required when pulsed power electronics are implemented. A bandwidth of at least 10 times that of the maximum fundamental frequency is needed
- All measurements shall be NIST-traceable (National Institute of Standards and Technology)

Energy Measurement

The measurement of electrical kinetic energy is performed by making voltage and current measurements, computing electrical power, and performing a gapless integration of power over time (Figure 1).
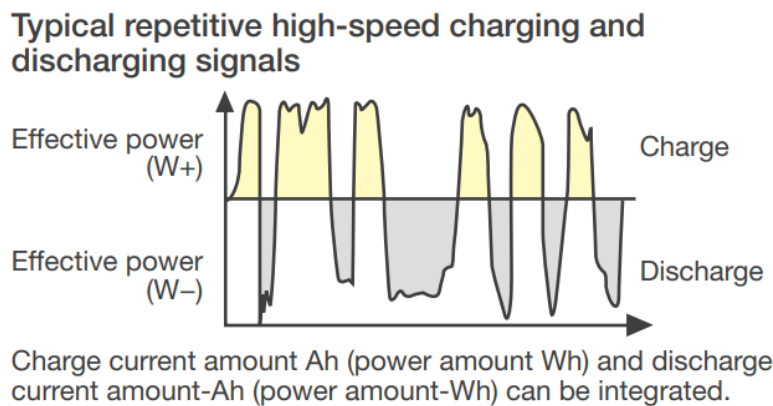

Figure 1 – Integration of power over time

Similarly, the measurement of mechanical kinetic energy in a rotating machine is typically performed by making torque and speed measurements, computing mechanical power and integrating power over time. The efficiency of the conversion electrical kinetic energy to mechanical kinetic energy is computed from the ratio of electrical input energy to the mechanical output energy. A power analyzer is a purpose-built instrument intended for making both the electrical and mechanical energy measurements (Figure 2). A power analyzer will provide highly detailed published accuracy specifications with NIST traceability (Figure 3). Power analyzers are often called out in standards documents as the preferred measurement devices for electrical measurements and are regularly found in the engineering laboratories of manufacturers and government agencies responsible for ensuring compliance. SAE J1634 presumes that computations for electrical energy measurement will be performed by a power analyzer.

Figure 2 – Multi-phase power analyzer

Voltage

DC	±(0.02% of reading + 0.05% of range)
0.1 Hz ≤ f < 10 Hz	±(0.03% of reading + 0.05% of range)
10 Hz ≤ f < 45 Hz	±(0.03% of reading + 0.05% of range)
45 Hz ≤ f ≤ 66 Hz	±(0.01% of reading + 0.02% of range)
66 Hz < f ≤ 1 kHz	±(0.03% of reading + 0.04 of range)
1 kHz < f ≤ 10 kHz	±(0.1% of reading + 0.05% of range) Add 0.015% × f of reading (lower than 10 V range)
10 kHz < f ≤ 50 kHz	±(0.3% of reading + 0.1% of range)
50 kHz < f ≤ 100 kHz	±(0.6% of reading + 0.2% of range)
100 kHz < f ≤ 500 kHz	±{(0.006 × f)% of reading + 0.5% of range}
500 kHz < f ≤ 1 MHz	±{(0.022 × f − 8)% of reading + 1% of range}

Current

DC	±(0.02% of reading + 0.05% of range)
0.1 Hz ≤ f < 10 Hz	±(0.03% of reading + 0.05% of range)
10 Hz ≤ f < 45 Hz	±(0.03% of reading + 0.05% of range)
45 Hz ≤ f ≤ 66 Hz	±(0.01% of reading + 0.02% of range) ±0.5 µA* *only direct input of 760902
66 Hz < f ≤ 1 kHz	±(0.03% of reading + 0.04 of range)
1 kHz < f ≤ 10 kHz	±(0.1% of reading + 0.05% of range)
10 kHz < f ≤ 50 kHz	±(0.3% of reading + 0.1% of range)
50 kHz < f ≤ 100 kHz	±(0.6% of reading + 0.2% of range)
100 kHz < f ≤ 200 kHz	±{(0.00725 × f − 0.125)% of reading + 0.5% of range}
200 kHz < f ≤ 500 kHz	±{(0.00725 × f − 0.125)% of reading + 0.5% of range}
500 kHz < f ≤ 1 MHz	±{(0.022 × f − 8)% of reading + 1% of range}

Power (PF=1)

DC	±(0.02% of reading + 0.05% of range)
0.1 Hz ≤ f < 10 Hz	±(0.08% of reading + 0.1% of range)
10 Hz ≤ f < 30 Hz	±(0.08% of reading + 0.1% of range)
30 Hz ≤ f < 45 Hz	±(0.05% of reading + 0.05% of range)
45 Hz ≤ f ≤ 66 Hz	±(0.01% of reading + 0.02% of range)
66 Hz < f ≤ 1 kHz	±(0.05% of reading + 0.05% of range)
1 kHz < f ≤ 10 kHz	±(0.15% of reading + 0.1% of range) Add 0.01% × f of reading (lower than 10 V range)
10 kHz < f ≤ 50 kHz	±(0.3% of reading + 0.2% of range)
50 kHz < f ≤ 100 kHz	±(0.7% of reading + 0.3% of range)
100 kHz < f ≤ 200 kHz	±{(0.008 × f)% of reading + 1% of range}
200 kHz < f ≤ 500 kHz	±{(0.008 × f)% of reading + 1% of range}
500 kHz < f ≤ 1 MHz	±{(0.048 × f − 20)% of reading + 1% of range}

Figure 3 – Example Power Analyzer Accuracy Specifications

Benchmarking Efficiency

EV powertrain systems are often comprised of multiple AC to DC, DC to DC and motor and inverter drive components, each component in the stage contributing to the overall system efficiency. Figure 4 shows an example traction motor and drive system comprised of a DC input, variable speed 3-phase inverter, and a variable speed motor.
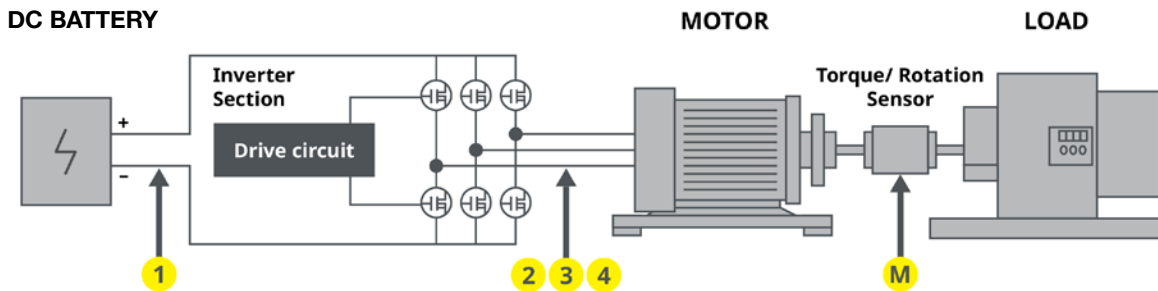

Figure 4 – Example Motor and Drive System

Measurement points 1-4 denote the points of electrical power measurement in the system, with point M denoting the measurement of mechanical output power. Power analyzers allow engineers to take high confidence measurements at each one of these stages, quantifying the efficiency of each component in the system (inverter, motor), enabling the maximization of overall powertrain efficiency. A power analyzer can also be used to evaluate the efficiency of other electrical components in the vehicle such as charging systems shown in Figure 5.
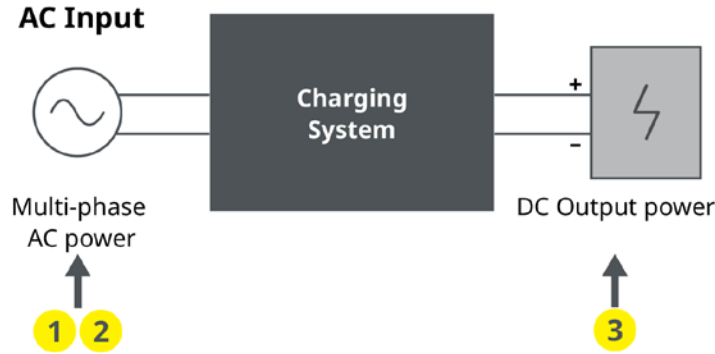

Figure 5 – Evaluating charging system efficiency

System Complexity

Power analyzers provide a concrete measure of efficiency throughout the system; however, each individual component carries its own complexity. Each sub-component presents unique engineering challenges to optimization and integration. A new motor control algorithm in the inverter might require the use of a positional feedback sensor such as Hall-effect, encoder, or resolver. As shown in Figure 6, the feedback from these signals are often high-speed, multi-channel, and require complex mathematics to decode position, direction, and speed.
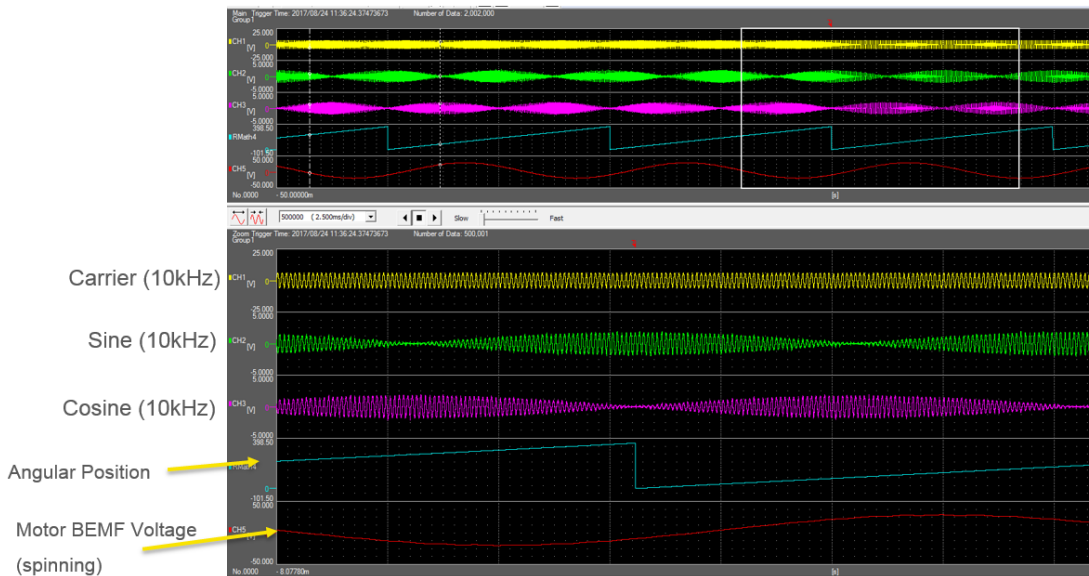

Figure 6 – Example resolver signal and position (carrier, sine, cosine)

Figure 7 shows an example output of an AC inverter driving a motor. Modern inverters use high-speed pulsed power electronics (PWM), resulting in complex high-voltage, high-frequency output waveforms of voltage and current. These signals present several engineering challenges such as harmonics, electromagnetic interference, and the ability to make high-voltage measurements in a safe manner.
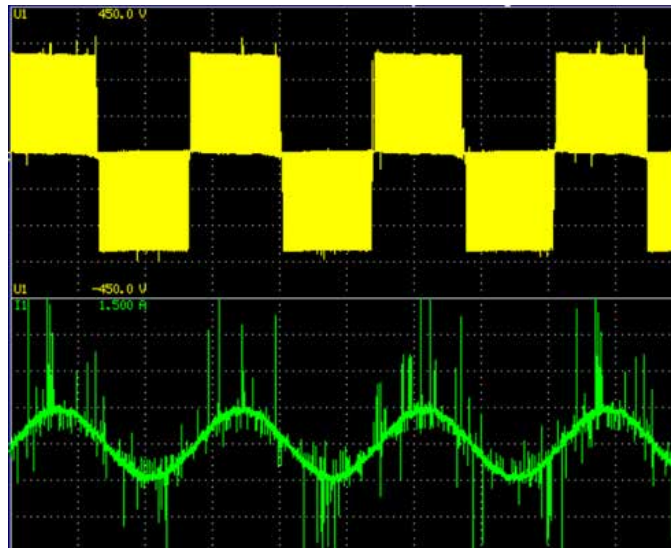

Figure 7 – AC Inverter output voltage and current waveforms

Modern embedded control systems employ digital communication networks such as CAN\FD to communicate between inverters, electronic control modules, battery management systems, on board diagnostics, and other sensors in the system (Figure 8). These signals require decoding and debugging for troubleshooting at the systems level.
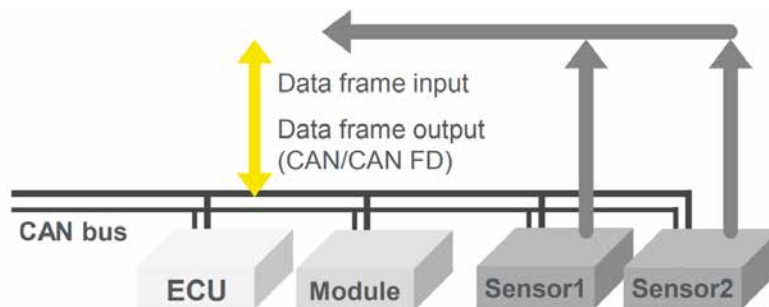

Figure 8 – Example communications network

Understanding how each of these subsystems are interacting and determining proper operation is key to optimizing the efficiency at each stage. Design, validation, and test engineers are faced with challenging questions when trying to understand the performance of the entire system. Examples of these challenges include:

 • Did the new motor control algorithm make a difference?

 • Is the motor feedback signal working properly?

 • Is the inverter properly communicating to the supervisory and control system?

 • Is there EMI causing a fault somewhere in the system?

Tackling Complexity

Optimization and integration of the individual components of a complex EV system requires instrumentation that is flexible enough to handle a wide range of signals not found in conventional oscilloscopes or data acquisition systems. A ScopeCorder is a purpose-built instrument for the development for electromechanical systems such as motors and drives. A modular design enables the evolution of the instrument as the engineering needs change. A unique array of digital and analog input modules combined with real-time math enable the decoding of complex sensor data such as encoders and resolvers. High-voltage, high-sample rate modules offer isolated inputs up to 1000V allowing safe measurements on complex pulsed power signals. Communication modules such as CAN/FD decode digital bus signals into engineering units for correlation with the rest of the system IO. Figure 9 shows the array of input modules including voltage, temperature, strain, frequency, acceleration, logic, and various digital communications.

Figure 9 – ScopeCorder system with array of input modules

A Comprehensive Measurement Solution

Standards such as SAE J1634 establish test methods that provide parity in the market as government agencies attempt to steer manufacturers towards more energy efficient vehicles. Precision power analyzers are a purpose-built tool for providing reliable mechanical and electrical energy measurements allowing manufacturers to confidently comply with standard testing procedures. The complexity of electric vehicles challenge engineers with a multitude of signals that conventional instrumentation does not easily accommodate. ScopeCorders provide a unique solution to mechatronic measurements and allow engineers to better answer the challenging questions that arise when analyzing the performance of an entire system. Yokogawa Test and Measurement is an industry leader in providing a full range of instruments for energy measurement and mechatronics development including power analyzer and ScopeCorders.

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