White Paper

Common Cable Faults and Their Detection in Heavy-Duty Incremental Encoder Systems

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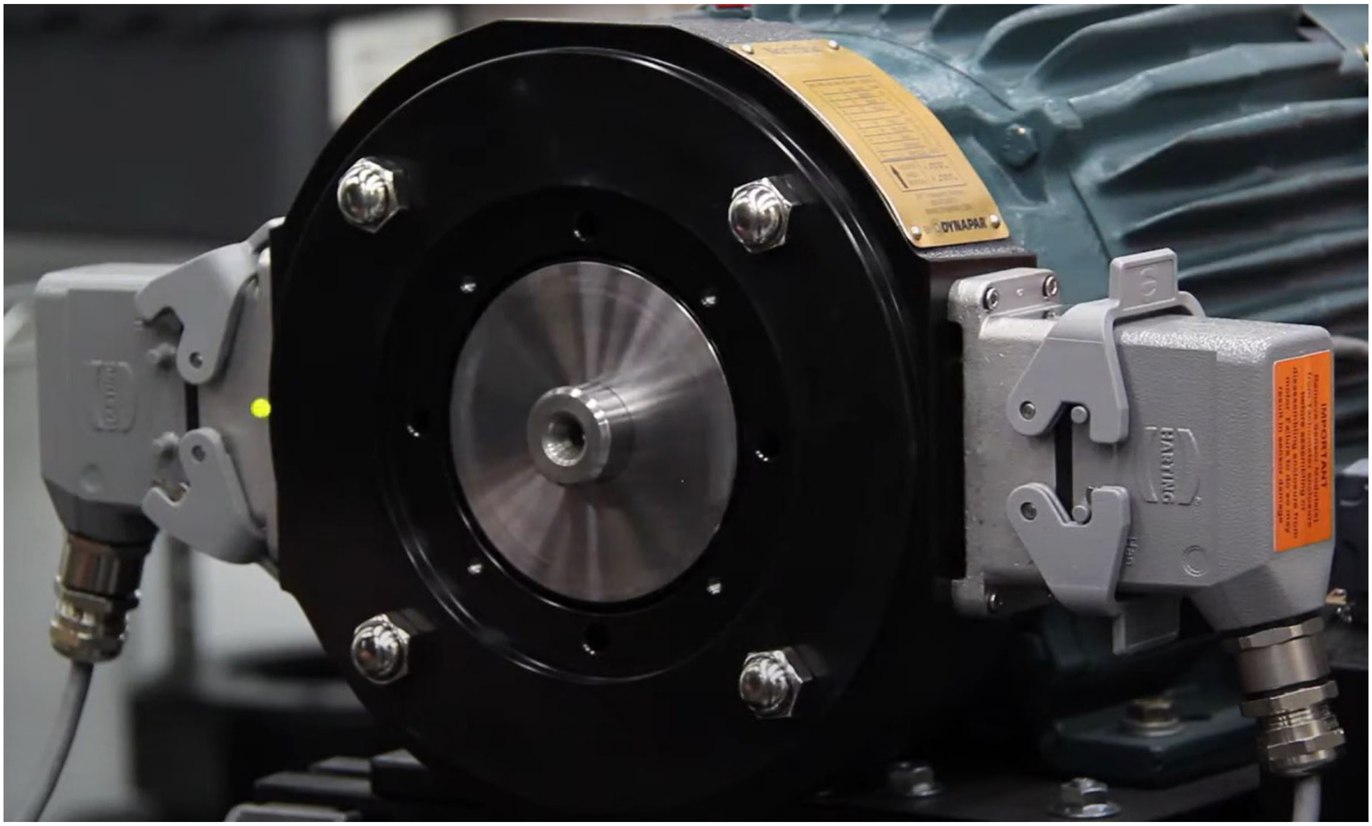

Common Cable Faults and Their Detection in Heavy-Duty Incremental Encoder Systems

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Summary: This paper gives an overview of common incremental encoder cable faults and their causes within the heavy-duty industrial environment. It introduces a method of automatic detection of such failures, which can indicate a cable fault and its specificity to quickly resolve it by a service technician, knowing what to look for and fix it. This method can detect non-catastrophic cable errors, which lead to signal degradation without total loss of function. These are often difficult to find and diagnose.

Introduction

Incremental encoders are used to measure the position/speed of motors as part of closed-loop motor control circuitry. These motors are usually big, and their unexpected stoppage causes significant downtime or material loss costs. In a steel plant, encoder systems fail as often as 4 times per year. This results in ~$350M of annual waste in the global steel industry alone. A similar level of waste can be found in oil and gas or mining industries. Major causes for encoder systems to fail are:

- Cable faults,
- Encoder-motor coupling slip,
- Encoder-motor shaft misalignment [1].

Encoder Supply Voltage

The encoder supply voltage drop might be of concern when using longer cables between the encoder and controls. The encoder supply voltage is often specified in the 5 V- 26 V range with minimum voltage to operate reliably at 5 V. Below 5 V, the encoder will start to malfunction, potentially outputting an erroneous signal or no signal. Encoder current draw is generally in the 100 mA – 250 mA range + current to feed output line driver, which might be in the range of 2 mA to 80 mA. This sums up to ~300 mA current flowing through DC supply wires [2].

Using 100 ft of standard 24AWG copper cable with 24 Ω/1000 ft Direct Current Resistance (DCR), 5 V supply voltage and 300 mA encoder current draw, the total cable voltage drop is 1.38 V which means the encoder is fed by 3.62 V. Such voltage is well under the limit for proper encoder operation and might cause intermittent or permanent signal faults.

$$Vencoder = Vsupply - 2 * I * Rcable$$
$$= 5V - 2 * 0.3A * 2.4\Omega = 5V - 1.38V = 3.62\text{V}$$

However, using a 24 V power supply and 500 ft of cable type above will yield a 7.2 V of cable voltage drop. In this case, the encoder is fed by 16.8 V, which is well above its minimum limit for proper operation.

Some modern encoders can measure the supply voltage at the encoder and warn the user if it is too low to operate correctly.

Current in Signal Wires

The encoder emits quadrature A B signals to detect the motor shaft position. Typically, a heavy-duty incremental encoder will emit 1024 pulses per revolution (PPR). Higher PPRs will allow for smoother motor operation and higher dynamics of motor control. Some encoders allow for user programmable PPR up to 20,000 PPR.

Two pulse trains, A and B, with 90° phase shifts, are used to distinguish between clockwise and counterclockwise rotation. The Z signal is a pulse generated once per full rotation, sometimes used for positioning purposes.

The A, B, Z signals voltage level is either 5V for Transistor-Transistor Logic (TTL) applications or 12-24V for High Transistor Logic (HTL) applications. HTL voltage level is equal to encoder supply voltage when high.

The voltage level (TTL or HTL), cable impedance and drive/encoder card input impedance define the ABZ signal wire current. The encoder power supply, which operates on Direct Current (DC), has two factors that impede current flow: the limits of the supply itself and the resistance of the cable connected to it. The line driver limits along with the cable impedance determine current flow for the ABZ signals because of the Alternating Current (AC) nature of those lines. Impedance is a combination of resistance and reactance. Reactance is a function of capacitance and inductance. Cable impedance is given by cable physical construction and length—moreover, impedance changes with signal frequency. However, the effect of changing impedance at different frequencies is negligible. With an encoder powered with 12V and located 100 ft. away from the drive, the effective RMS voltage measured on signal A is equal to 7.7V at 150kHz and 7.5V at 1kHz. The cable reactance is predominantly capacitive; it decreases with higher frequencies.

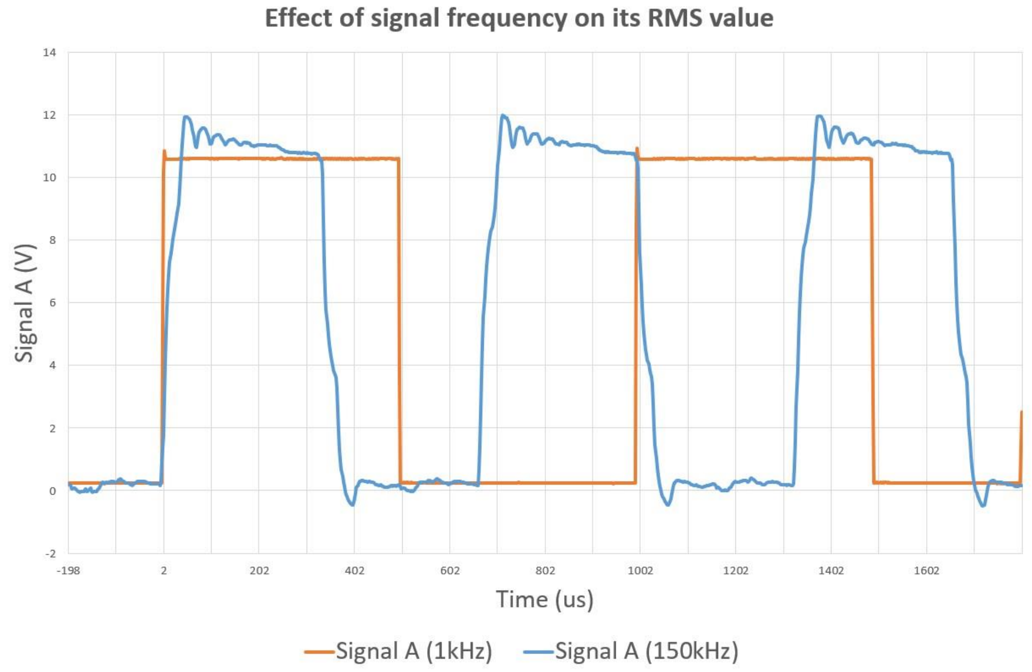

Figure 1. Signal A – voltage measured at drive at 150 kHz vs. 1 kHz, signal RMS is 7. 7 V vs. 7.5V respectively.

For optimal signal quality it is recommended to keep the signal current as high as possible, as this will improve the signal-to-noise ratio. However, there are limitations on the maximum current flowing through signal lines. The encoder line driver maximum current limits are typically 40 mA to 100 mA per signal. Theoretically, with 6 signal lines, the line driver current draw could be 6 x 100mA = 0.6A. However, the encoder power supply is often limited to a max. of 200 mA [3]. When using an external power source, this limit might be higher. Encoder electronics can consume 150 mA, leaving only 50 mA for the supply line driver. To prevent undervoltage to the encoder and overloading the power supply, the current to each signal line shall be limited to approximately 5mA.

To calculate approximate current flow at signal frequency of 1kHz, using 100 ft of standard 24 AWG cable with a nominal characteristic impedance of 100 Ω and drive input impedance of 22 kΩ, the following formula can be used:

$$I_{A\,signal} = \frac{V_{A\,signal}}{Z_{cable} + Z_{drive}} = \frac{5V}{100\Omega + 22000\Omega} = 0.2\,mA$$

The drive impedance significantly influences current flow, as the current is much lower than the optimum 20 mA. Due to the large range of drive input impedance (1kΩ – 30kΩ) using a 1kΩ termination resistor makes getting the signal current closer to the optimal range.

$$I_{A\,signal} = \frac{V_{A\,signal}}{Z_{cable} + \frac{Z_{drive} \times Z_{termination}}{Z_{drive} + Z_{termination}}} = \frac{5V}{100\Omega + \frac{22000\Omega \times 1000\Omega}{22000\Omega + 1000\Omega}} = \frac{5V}{956\Omega} = 5\,mA$$

Differential A, B, Z Channels

Encoder cables are often exposed to external sources of noise, which negatively influence signal quality. A common noise source is a motor power cable installed near the encoder cable. The longer the cable, the more noise is induced on it. To eliminate this issue, differential signal channels are used.

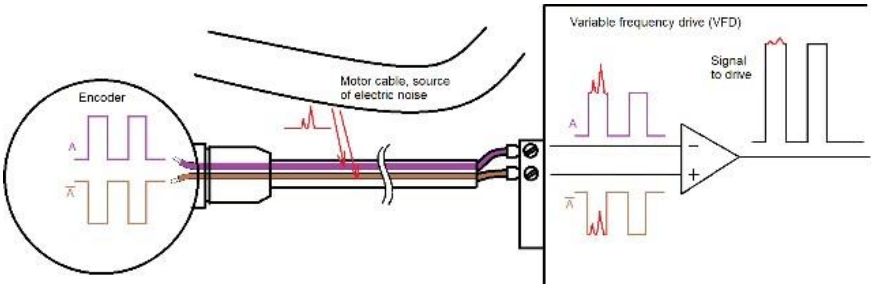

Figure 2. How differential signals cancel external noise

In principle, the noise generated in the external source is induced both on A and A_NOT signals with the same polarity. The drive input circuitry subtracts A_NOT from A, which results in an output signal with double the amplitude of the original signals while canceling out the external noise (see Figure 2).

Practically, one differential wire is physically further away from the noise source than the other wire, which causes a slightly different amplitude of induced noise in the differential pair (see Fig 2. A_NOT wire is physically further away from the noise source than A wire). That results in a minor amount of noise still present after subtracting differential signals. To avoid this, twisted differential pair wires are used, which physically equalize the distance from the external noise source. Thus, the induced noise has equal amplitude in both wires resulting in better noise cancellation.

Differential output encoders can be wired as single-ended, leaving the inverted signals disconnected. The differential input circuitry of the drive or card will still be able to distinguish the pulses, simply subtracting the existing signal and 0V, which yields the pulses present in the single input. However, using differential pairs is highly recommended in noisy industrial environments to avoid false or missing pulses.

Given the analog nature of the drive's or encoder card's differential input, if one of the differential signals is accidentally missing, the card will continue to work and gives no warning (See Figure 3). However, the noise-canceling feature of differential pair is compromised, and signals include all the external noise induced. The cable open circuit detection feature built into the encoder can detect the open in one of the differential signals and warn the user so the cable can be fixed and noise-canceling restored.

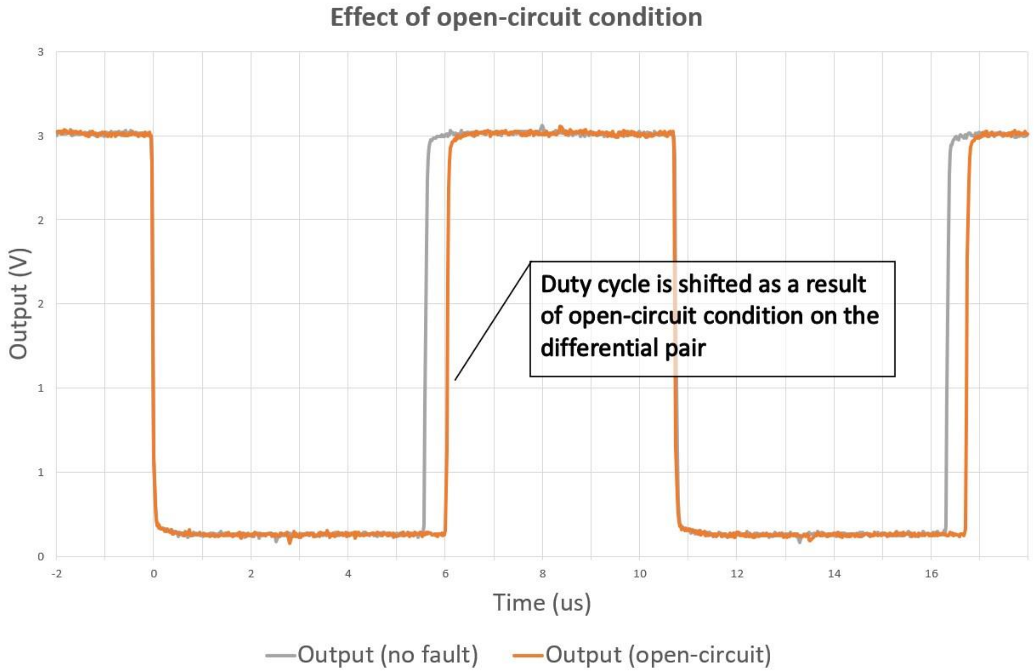

Figure 3. Output from differential comparator after subtracting signals. Grey - both differential signals present. Yellow – one differential signal is missing. Open-circuit duty cycle: 43.66% (high) / 56.34% (low). No fault duty cycle: 48.06% (high) / 51.94% (low). Measured at 93kHz and 12V supply voltage.

Example Encoder with Cable Fault Detection Built-In

The HS35iQ encoder with PulseIQ™ Technology utilizes the principles above to detect a cable open state and other common encoder fault conditions. [Learn more about the HS35iQ encoder here]()

Device Characteristics
Model Number HS35IQPROGR01921R1
Order Number 12345678-0017
Date Code 01522
Model Attributes [0003]

Firmware Characteristics
Firmware Version 1.1.1.0
Firmware Build Time Apr 14 2022 11:40:37
Firmware Checksum [C1C6]

System Data
Current Run Time 0:00:42:00.084
Current Temperature +27.0 °C

Life Cycle Data
Total Operating Time 0:00:44:27
Total Circular Distance 3,348 ROT
Boot Counter 11
Number of Electronic Faults 10
Number of Temperature Faults 0
Number of Cable Faults 4
Number of Coupling Slip Faults 0

Position Data
Pulse Count 872
Position Status OK
Circular Speed +0.00 RPM

Electronic Fault Monitoring OK
Coupling Slip Fault Monitoring OK
Cable Fault Monitoring ERROR
Temperature Fault Monitoring OK

Notifications
```
07:39:00.848 Connecting device ..... succeeded
07:39:00.881 Device connected
```

Image 1. HS35iQ hollowshaft encoder with PulseIQ™ Technology

Degraded Signal

In general, electronic devices use electrical signals to transfer information from a source of information to a consumer of this information.

For incremental encoders, electrical signals of A, B and Z channels carry position information from the source (encoder) to the consumer (motor drive). Information must travel a certain distance from the source to the consumer, and for this purpose, a suitable medium must be used. For electrical signals, a cable is used, which consists of conductive wires separated by an insulating material. The cable, by its nature, causes some inevitable degradation of the transferred signals, namely:

- Transient effects caused by cable characteristics,
- Signal reflections caused by improper cable termination.

Figure 4 localizes individual effects on the measured encoder signal of 90 kHz when using a 400 ft long cable.

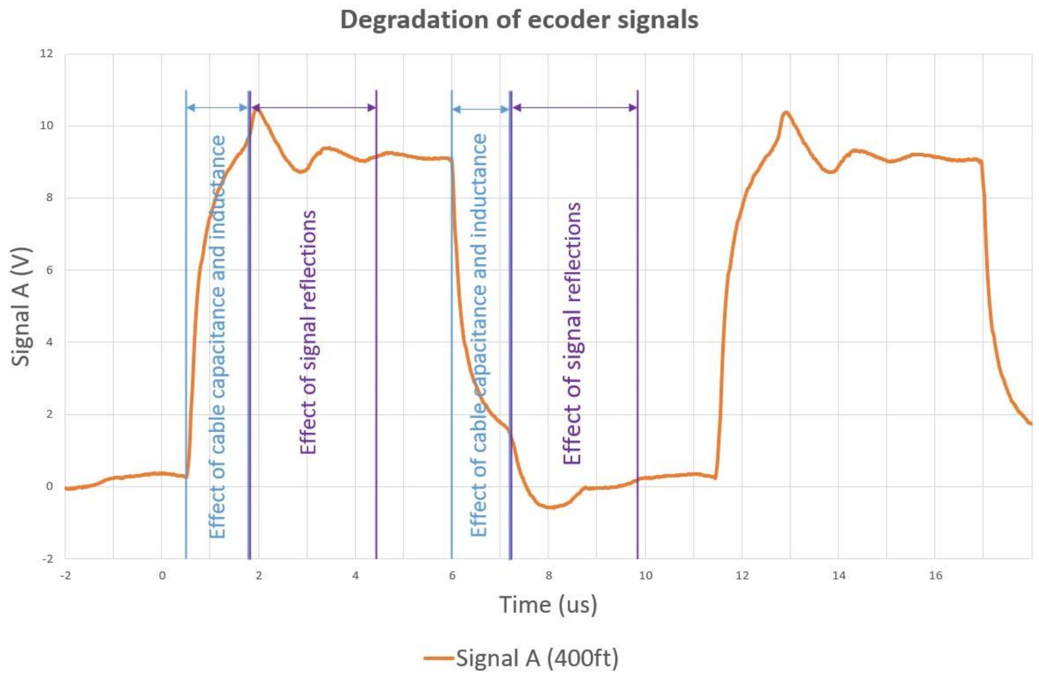

Figure 4 Degradation of encoder signals in 400 ft cable

To obtain good signal quality at the motor drive side, selecting a cable with appropriate characteristics is essential. It is advised to use a cable with twisted pairs of 24AWG wires, and a characteristic impedance of 100Ω.

As previously explained, twisted-pair helps to eliminate the effects of common-mode noise. Second, a large diameter wire (24AWG) will reduce DC voltage drop over the cable length. Lastly, characteristic impedance speaks of its effective resistance to electrical current, or in other words, the impact of the ohmic resistance, capacitance and inductance distributed along the cable.

Distributed capacitance and inductance of the conductors in cable do not affect DC signals due to their static voltage levels. On the other hand, AC signals are affected by distributed capacitance and inductance within a cable. This reactance can result in significant transients every time a change in voltage or current occurs. Transient effects result from energy stored in the capacitance and inductance of the cable. In general, capacitors store energy in the form of electrical charge and inductors in the form of a magnetic field. The amount of energy stored in an inductor depends on the current flow in the circuit, and the amount of energy in a capacitor depends on the voltage level across it [3].

If the voltage level, or current flow in the cable changes, so will the energy stored in the distributed capacitance and inductance in the cable, thus forming a transient effect. In the encoder, the current flow of the signals changes far less than their voltage level; therefore, the result of cable capacitance will be more pronounced and cause degradation of the encoder signals. This is evident from the following figure (Figure 5).

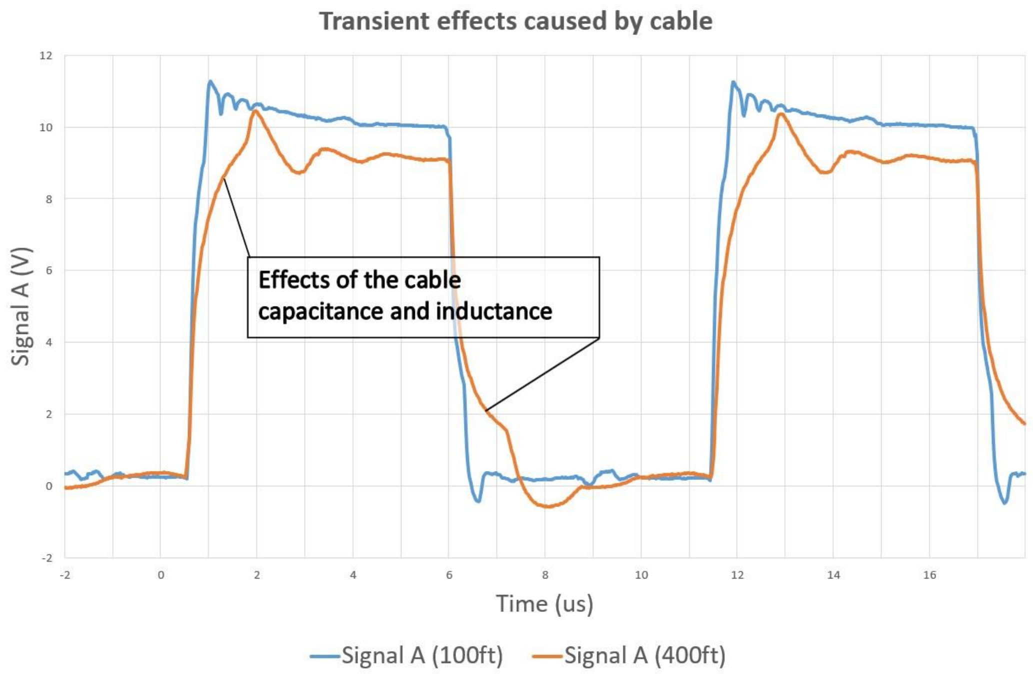

Figure 5. Longer vs. shorter cable and its effect on signal degradation

As presented in the previous figure, the duration of the transient effects in the cable is directly proportional to cable length. In the short cable, there is less distributed capacitance than in the long cable, and so the duration of the transient effect is:

- For 100ft cable ~300ns, and
- For 400ft cable ~1200ns.

Another cause of signal degradation in long cables is the result of improper cable termination. Proper cable termination is represented by a termination resistor with a value matching the cable's characteristic impedance. Figure 6 shows a comparison of the signals from terminated and unterminated cables.

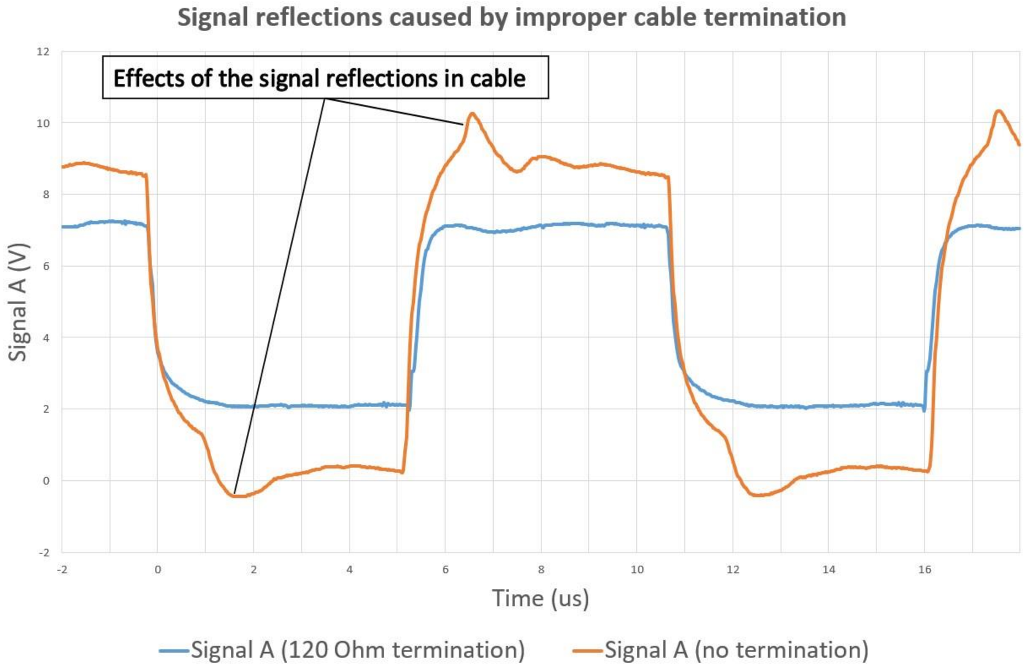

Figure 6. Signal degradation in terminated vs. unterminated cable

It is essential to know the overall duration of transient effects in the cable because it limits the maximum frequency of the encoder signals. When approaching the maximum frequency, the stable part of the pulse duration is reduced to a minimum. The signal would consist of transient effects only, thus making it unusable for the motor drive to recognize encoder position information.

It is essential to understand that the duration of the transient effect is not related to the signal frequency. Instead, the duration of the transient effects is related to the cable characteristics (capacitance and inductance), cable length and termination, as explained previously in this chapter. The following figure speaks of the situation when the signal frequency is increased from 35kHz to 135kHz, but the duration of the transient effect is unchanged.

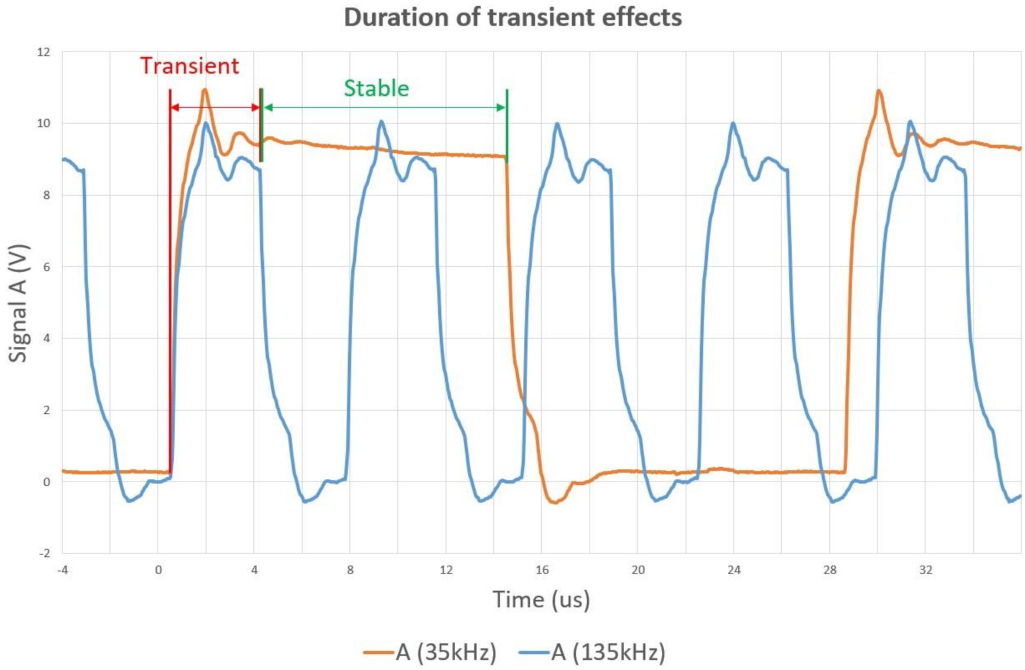

Figure 7. Duration of transient effects does not change with signal frequency

Suppose the application requires a very long cable. In that case, reducing the encoder PPR (pulses per revolution) is recommended to keep the frequency of encoder signals below the maximum limit set by the cable capacitance and cable termination.

In any case, here are some general recommendations for achieving good signal quality:

- Select a cable with low nominal capacitance
- Terminate the cable properly.

Sometimes it is not possible to properly terminate the cable since the current consumption of the encoder is increased by adding a termination resistor, and the application power supply may not be sufficient for the higher current demand. If the power supply hits the current limit, it will cause a voltage drop in the encoder power supply and may suspend encoder operation.

Another case when proper termination is not possible is when the addition of a termination resistor will increase the current flow so much that it exceeds the recommended maximum current per channel of the line driver inside the encoder. This may cause encoder overheating and damage. In such cases, it is recommended to use a termination resistor of greater value, ranging from 1kΩ to 5kΩ. This will sufficiently maximize current flow of individual signals to achieve better signal quality while keeping the overall current flow in the range of safe operation.

Open and Short Circuit Detection

As discovered by the market research, encoder cable faults are a common cause of closed-loop motor control systems failing. Proper cable design considerations, as described above, are the key to success, but sometimes the cables will get accidentally broken, loosened, or short-circuited during operation. As the broken cable is not always visually detectable, the technician needs to troubleshoot and understand the source of failure (motor, coupling, encoder, cable, drive). To point the technician directly to the root cause, cable open and short circuit detection by encoder might be helpful.

Detection measures the current on each signal line and supplies this information to the microcontroller. With some level of simplification: if the signal current is 0 mA, an open circuit is reported. A short circuit is reported if the signal current is at line driver maximum (40 mA or 100 mA).

It is generally more difficult to distinguish between an open circuit and normal operation if the standard operating current in signal lines is very low (e.g., 0.05 mA). This might happen when the drive input has a high impedance, and no termination resistor is used. Moreover, it is more difficult to detect an open circuit far away from the encoder end than to detect one closer to the encoder. This is due to the higher amount of induced noise on longer cables acting as if some current was flowing through the signal line.

The limiting factor for detecting short circuits is again related to the standard operation current flowing in the signal lines. If the termination resistors are of low value (e.g., 100Ω), this can result in current that will exceed the max limit of the line driver. It is impossible to distinguish between a short circuit and normal operation in such a case.

The shorts and open detection algorithm work best when the signal current is in the optimum range, as described in the beginning of the paper.

Conclusion

Designing a proper connection between encoder and drive is quite a complex topic. However, if best practice is followed, most signal related issues can be avoided:

- Use 24AWG twisted pair shielded cable
- Use 12-24V encoder power supply voltage
- Connect all differential signal pairs
- Terminate the cable at the drive end using a 1kΩ-5kΩ resistor
- In high-speed or long cable applications, use a lower PPR

If signal wires in the cable get broken or short-circuited during operation, some encoders can detect and report the issue to the technician. If the voltage drop on a long cable is causing an insufficient power supply to the encoder, this can be reported to a technician as well.

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About Dynapar

Dynapar is an industry leading supplier of encoders, and resolvers. From small kit encoders to large mill-duty tachometers, Dynapar has a strong market presence in a wide range of industries including steel, paper, elevator, oil and gas, aerospace & defense, medical, material handling and industrial servo manufacturing. Dynapar offers a broad array of encoders and resolvers through our well established Dynapar™, Hengstler™, NorthStar™ and Harowe™ brands. Dynapar supports global customers with local sales and production locations in USA, Germany, Slovakia, China, and Brazil.

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