Leveraging Custom Linear Solenoids in OEM Applications

TLX TECHNOLOGIES
Innovative Electromagnetic Solutions

Leveraging Custom Linear Solenoids in OEM Applications

Wayne Groth • Jeff Rogala • TLX Technologies • Pewaukee, Wisconsin

Linear solenoids are widely used in OEM designs for their ability to deliver efficient short-stroke actuation. Standard solenoids are sometimes sufficient. However, because every OEM design has unique requirements and application challenges, customized solenoids often offer technical benefits that allow engineering teams to bring better products to market faster, with higher value for the end customer. More specifically, custom solenoids can deliver better efficiency than off-the-shelf designs by tailoring materials, functionality and design to application requirements. Custom solenoids can also be more cost-effective by eliminating extraneous elements and optimizing those that are integrated.

This brochure examines customizable solenoid features and illustrates how they can help engineers meet key performance objectives more effectively.

A solenoid is an electromagnetic actuator that uses a multi-turn copper wire coil surrounding a moveable ferrous armature (or plunger) to convert electrical energy into mechanical energy.

When electrical current flows through the coil's wire, a strong magnetic field (flux) is created. Steel flux plates located at the bottom and top of the coil assembly help carry the flux. The solenoid housing, usually made of a ferrous material (steel, iron, magnetic stainless, etc.) surrounds the coil to concentrate the coil-generated magnetic field. No matter the housing arrangement, the armature is moved by this field to provide mechanical force for work output.

Customized solenoid performance parameters can satisfy these OEM design objectives:

- Targeted force and stroke
- Efficiency and power consumption
- Heat dissipation
- Valve integration
- Positioning
- Package size constraints
- Environmental protection
- Fast response time
- Zero power consumption

Throughout this brochure, features customizable to satisfy design objectives are cross-linked accordingly.

The following solenoid components can be customized to meet OEM design requirements:

- Coil, including coil resistance, power usage, operating voltage and subcomponents including wire material, winding design, optional overmolding and terminal adaptations
- Armature, including its material, face geometry and sealing features
- Housing, including frames, mounts, optional tube construction, and optional incorporation of permanent magnets (used in latching solenoids)
- Controls, drive circuits such as circuits to ensure safety upon power failure, diode-resistor circuits, pulse-width modulation (PWM), peak-and-hold schemes, position-control circuits, and power supply (including rectified AC, DC, battery, capacitive discharge) operation
- Springs, which can be added to the armature end to return it to its original position once power is removed. In other designs, a spring may serve other operational functions. (One caveat: Adding a spring to a solenoid design reduces overall holding force, so care must be taken to prevent total force cancelation.)

For the definitions of basic technical terms used in this brochure, visit **www.tlxtech.com/understanding-solenoids/glossary**.

Solenoid coil customization

❶ **Coil material.** Two main solenoid coil materials exist. **Copper wire** is heavier and more costly than aluminum due to its scarcity, but it has superior electrical and thermal conductivity; is more energy efficient; has high tensile strength; withstands thermal changes; plus exhibits fewer inter-metallic growths and higher mechanical stability than aluminum. **Aluminum wire** is lighter and less expensive, but a larger wire gauge is required

Basic solenoid operation

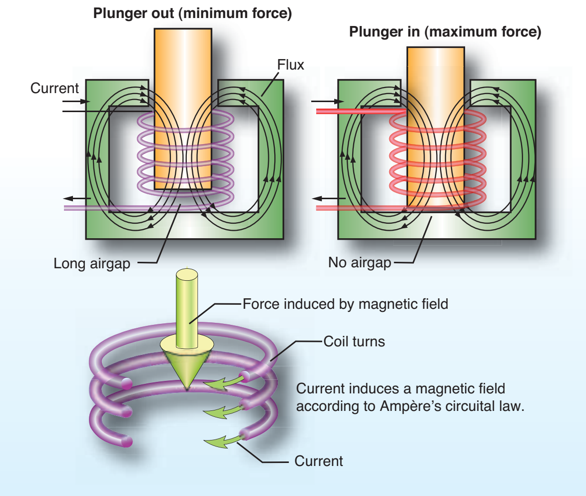

Figure 1: Solenoids leverage Ampere's Law and Faraday's Law: Applying current to the coil produces a magnetic field that draws in the armature, reducing the airgap and flux path reluctance – which strengthens the magnetic field as well as output force. Solenoids generally consist of a housing core, coil, and armature.

to compensate for lower conductivity. It also expands and contracts with temperature changes, is less ductile, and can react with air — which can cause connections to overheat and fail. Copper is predominately used in solenoid coils, but there are currently advancements in aluminum composites that may one day make it competitive with copper.

❷ **Wire type. Round wire** is commonly used for solenoid coils and is the most efficient wire type for winding around bobbins. It also lends itself to high-speed automatic winding. Square wire is common on large motors but not in solenoids, as it's impossible to get small-gauge square wire to precisely lay in coil windings.

❸ **Wire finishing. Insulation** is available in many classes and is chosen to withstand application temperatures and chemicals. Copper-insulated magnet wire rated up to 180°C can be soldered. Insulation is burned off during soldering, so the wires don't need to be stripped when attaching terminals. Wire rated for temperatures exceeding 180°C cannot incorporate soldering without mechanically or chemically stripping. Instead, such wire accepts resistance welding to burn insulation off and create a connection.

❹ **Winding techniques.** **Precision-wound coils** are wound so that each layer of wire lies exactly next to the previous layer, which is essential to a compact design. (Maximizing the amount of copper in the volume maximizes magnetic force.) In contrast, random-wound coils are used with small-diameter wire or where the required force doesn't conflict with space constraints.

❺ **Coil types.** A common solenoid coil type is **bobbin wound** — in which coils use a molded bobbin made from engineered plastic. The bobbin material must have the same temperature rating as the coil. In contrast, **freestanding** or **bonded** solenoid coils are often coated with an additional layer of heat or solvent-activated adhesive that bonds the wire together.

Solenoid coils are secured and protected from the environment in three ways — tape wrapping, encapsulation, or potting.

Tape wrapping holds bobbin-wound magnet wire. Tape-wrapped coils provide limited environmental protection and heat transfer capabilities.

Encapsulating coils increase environmental protection. Encapsulated coils (thermoplastic injection or potting) are used in applications for maximum environmental protection. Thermoplastic injection molding lends itself to faster cycle times, more design options, and lower cost. Potted coils have the potential for better heat transfer because there are specific compounds engineered to improve thermal heat dissipation.

❻ **Coil terminations.** A variety of coil terminations exist including integrated connectors, flying leads, flying leads with connectors, and customer-specific terminations. The options are endless and determined by the requirements of the application.

Solenoid armature customization

❶ **Material.** Solenoid armatures are made of magnetic material. The most suitable material depends on application requirements. For example, if an engineer is designing a solenoid valve through which drinking water runs, it must be a magnetic material that will not rust — such as a magnetic stainless steel.

❷ **Armature configuration.** Changing the geometry of the armature changes the shape of the force curve. For any application, various armature designs must be modeled to ensure a force curve sufficient for the load curve.

A flat armature face is typically used for shorter stroke and higher force applications — making such a configuration suitable for latching solenoids. In contrast, a conical armature face is used for longer stroke and higher force applications. A third option — a radial armature face — is used for longer strokes and has the highest potential force at the longest stroke. All three of these geometries can be incorporated into one armature to shape the force curve needed for an application. A conical or radial armature face configuration is typically used for proportional valves. Application stroke and holding force requirements determine the most suitable design.

Note: Commonly known as the pole stop, the flux pole is the stationary part that the armature contacts

Armature effect force-stroke curve

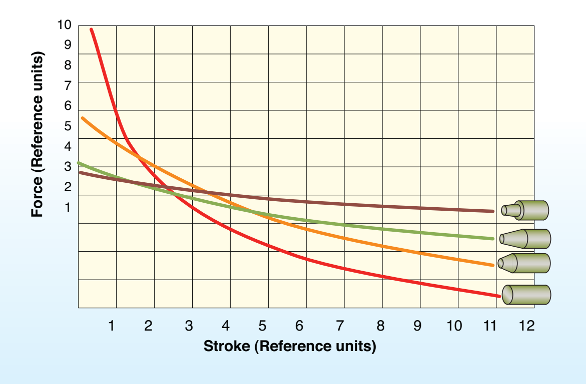

Figure 2: Shown here is the effect that armature type has on a solenoid's force-stroke curve.

Cost-effective open-frame solenoid

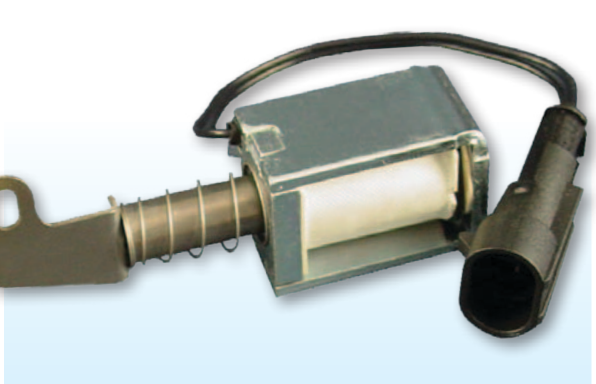

Figure 3: Shown here is an open-frame solenoid. These can be designed for latching or non-latching applications.

when pulled in. Its geometry must marry with that of the armature, though in conical and combination-shaped designs, 100% contact is not necessarily the rule. Flux-pole design is determined by the application's stroke and holding force requirements.

Solenoid housing customization

❶ **Subtypes.** Open-frame designs are suitable for applications that have no significant environmental threats (such as dirt or fluid). Such designs can incorporate a simple U frame consisting of bent or stacked C-shaped plates — sometimes laminated for AC solenoids (to isolate Eddy currents to minimize their heating effect) — to concentrate the magnetic field. For some applications that expose the solenoid to moderate contamination, open-frame solenoids can be used in conjunction with an encapsulated coil — though open-frame housings cannot be potted.

Tubular or cylindrical-type solenoid housings are more magnetically efficient and protect the solenoid's inner workings. Tubular-enclosed housings are the most versatile as they can be shortened, lengthened, and easily made larger or smaller — and potted if needed.

❷ **Materials.** The housing is constructed of magnetic material (such as iron, steel, magnetic stainless, etc.). Additionally, various surface treatments (such as plating, anodizing, etc.) can enhance corrosion protection.

❸ **Mounts.** Common options are threaded nose, wing, flange, and welded bracket mounts, though customized iterations — dictated by what's best for a given application — are endless.

Permanent magnets. The decision to incorporate permanent magnets into the solenoid housing is determined by the application's function. (See Customized solenoids with latching functionality.)

Proportional control of a solenoid

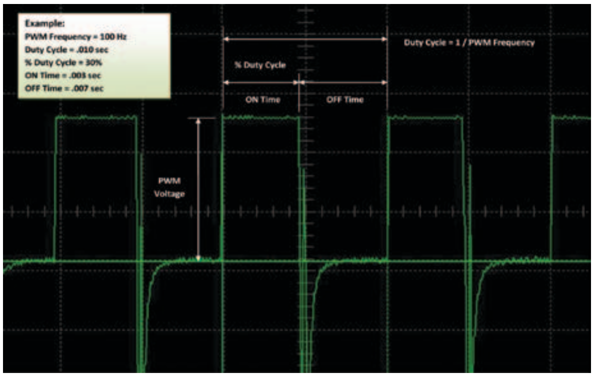

Figure 4: Shown here is a pulse-width modulated supply voltage used for proportional control of a solenoid.

Force versus stroke under proportional control

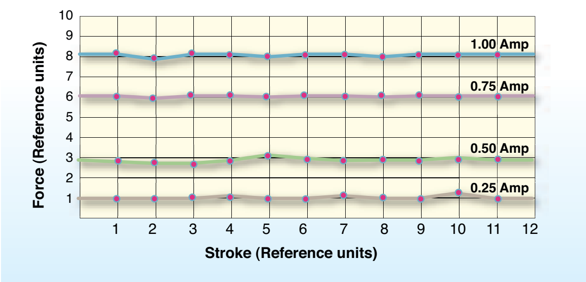

Figure 5: By converting an electric control signal into a proportional mechanical force, proportional solenoids deliver varying position and force. Shown here is the force curve for a proportional solenoid. Optimized armature and pole pieces yield a flat curve that in turn allows predictable position and force control.

Solenoid controls and drive circuits

Solenoid drive circuits and connectivity can be customized for many applications and designed for AC or DC power supply. Solenoid circuits can also ensure safety upon power failure; they are sophisticated controls, often improving solenoid output performance and allowing for size reductions.

Pulse width modulation and proportional operation
Widely used in solenoid control is PWM, in which voltage is switched on and off at a given frequency. Under such control, the solenoid's duty cycle is defined as the amount of time that voltage is on during a given time period. It is expressed as a percentage: For example, a 50% duty cycle indicates that voltage is switched on for 50% of the time, and switched off for the rest — for time-averaged voltage that is 50% of maximum supply voltage (and current to the solenoid that is 50% of maximum current).

PWM signals are used for proportional control — such as proportional hydraulic or pneumatic solenoid valves or position control.

Digital control — proportional solenoid-valve operation
Proportionally controlled solenoids are used in fluid-power valve applications to proportionally control flow (or pressure) from zero to maximum flow as a function of duty cycle. At zero duty cycle, the solenoid is stationary, the valve is closed, and flow is zero. At 50% duty cycle, the solenoid moves through full stroke and opens the valve. The valve is only allowing full flow 50% of the time, so the time-averaged flow, in theory, is 50% of maximum flow. This type of control is called digital because the valve is fully open or fully closed — On or Off.

Position control — proportional current operation
In contrast with digital control (in which the solenoid moves full stroke and is held at this position for some period of time), position control of a solenoid moves it from zero to full stroke as a function of the time-averaged current applied. At 50% duty cycle, the solenoid is supplied 50% of the current and, in theory, will move 50% of full stroke.

Current-controlled solenoids can be used for linear position control and also in hydraulic and pneumatic solenoid valves.

Two design elements are critical to proportional position control — low hysteresis and a relatively flat force-versus-stroke curve at a given applied current. Both boost solenoid predictability, repeatability, and command response. The incorporation of bearings reduces linear friction to minimize hysteresis; a flat force versus stroke curve is achieved by proper design of the armature and pole pieces.

Peak-and-hold solenoid control
Peak-and-hold solenoids are utilized when an application requires faster actuation times, lower average power consumption, lower heat generation, or smaller package size. Here, higher current is applied to the solenoid at its open or maximum airgap condition. Once the solenoid has completed its travel to the closed or minimum-airgap position, current is reduced to a hold current level, to maintain the solenoid in this position until removed. The current amplitude and time duration of peak-and-hold drive signals are customizable to application requirements.

Customized solenoids with latching functionality

Following are customizable solenoid elements that can be used to optimize latching functionality:

Flat armature	Permanent magnets	Springs	Residual magnetism

Permanent magnet (PM) latching solenoids utilize permanent magnets in conjunction with the solenoid coil to maintain the position of the plunger with no current applied. The permanent magnet generates a small magnetic flux in the magnetic circuit generating an attraction of the plunger and the fixed pole piece with no power applied. When a short pulse of electrical current is applied to the coil, the resulting electromagnetic flux generated by the coil can either add to or subtract from the permanent magnet flux, depending on the polarity of the applied current.

In applications where the load extends the plunger away from the fixed pole, latching solenoids can maintain the extended or retracted position without consuming continuous power. In applications where there is no load to act on the plunger, a spring can be used to hold the plunger in the extended position. In either case, a pulse of current is applied to generate magnetic flux to add to the permanent magnet and move the plunger to the fixed pole piece. When current is removed, the magnet holds the plunger latched. Conversely, applying a reverse polarity pulse cancels the magnet flux to allow the load or spring to release the plunger and move to the extended position.

Residual magnetism (RM) latching solenoid actuators operate in much the same way as do permanent-magnet latching actuators. However, RM actuators remain latched without the use of permanent magnets. RM latching actuators offer the same benefits as PM latching actuators by consuming no power, producing no heat, and generating no electrical noise while in the latched position. RM latches utilize the inherent residual magnetism common to all DC actuators that has been enhanced through special internal design features to provide latching force without permanent magnets. Here, a short pulse of electrical current of either polarity pulls in and latches the plunger to the fixed pole piece. Unlatching the actuator is accomplished by applying a pulse of lower current in the opposite polarity.

Note that conventional solenoids must maintain current (consume power) for the full on cycle; in contrast, latching solenoids move with a pulse of current and are turned off (consuming no power) for the duration of the on cycle. Conventional solenoids are also restricted to generating forces up to a 100% duty cycle and may be subject to heat dissipation problems. Latching solenoids can be turned off during most of the on cycle, allowing the use of a higher

Latching solenoid subcomponents

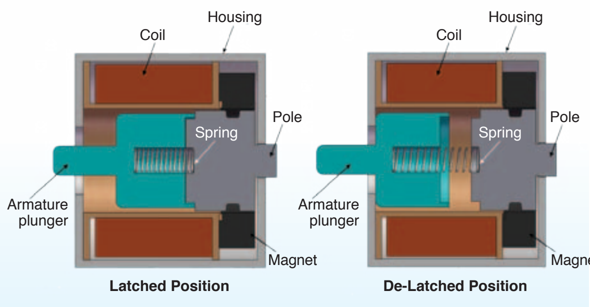

Figure 6: A pulse of current is applied to generate magnetic flux to add to the permanent magnet and move the armature to the fixed pole piece. When the current is removed, the armature is held in the latched position by the permanent magnet. Conversely, applying a reverse polarity pulse will cancel the permanent magnet's flux, allowing the load or spring to release the armature and move to the extended position.

current pulse for faster operation and generating higher pull force without the excessive power consumption or heat generation of a conventional solenoid. In addition, the possibility of applying a higher current to generate more force may allow for a smaller actuator to be used in an application and offer the potential benefit of overall cost reduction.

While latching actuators can offer performance advantages in a variety of applications, latching actuator technology may be unsuitable where the actuator is required to return to a known position upon power failure. Since latching actuators need to be powered to change state, the actuator would remain in the position it was in when the power failed. However, it is feasible to include a drive circuit with an energy storage feature in the control circuitry to allow the actuator to be positioned properly in the event of a power failure.

Both PM and RM latching actuators can be custom designed in either open frame or tubular solenoids as push, pull, or bi-stable (push-pull) arrangements — or in two- or three-position configurations

Constant-current versus latching solenoids

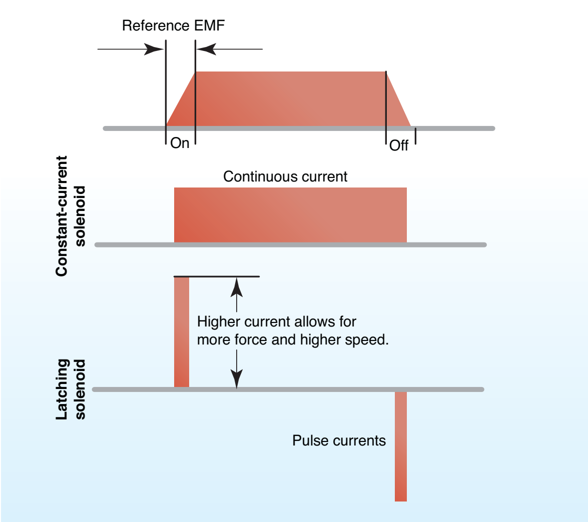

Figure 7: Conventional solenoids must maintain current (and consume power) for the full on cycle, while latching solenoids move with a pulse of current and then consume no further power. Compared here is the power consumption of a conventional constant-current solenoid to that of a latching solenoid. The response time to move the armature is the same for both solenoids.

depending on application requirements. In addition, myriad drive circuits ranging from simple diode-resistor circuits to more complex PWM current control circuits can be used to maximize cost effectiveness and efficiency.

Design Objective: Valve integration

Solenoids in fluid-power applications are integrated into the valve to make a single unit applied to the control of fluids, air, gases, steam, and other fluids. These solenoid valves can open, shut off, hold, or direct fluid flow in an application.

Two of the most common types of fluid control valves are direct-acting and pilot-operated. In direct-acting valves, the force of the solenoid acts to directly open or close the valve's orifice. The valve can be designed as normally open or closed in the de-energized position. Once energized, the solenoid either opens or closes the orifice until power is no longer applied. Flow and pressure of the media are limited by the power and size of the solenoid.

In pilot-operated valves, the fluid pressure assists the solenoid by providing a pressure differential to open the valve's orifice. The advantage of the pilot-operated valve is that, due to the smaller force required of the solenoid to open the valve's orifice, a smaller solenoid and shorter stroke can be used.

High-speed, high-temperature operation, and latching technologies can be designed into solenoid-controlled valves. A combination of all three technologies can be used in fluid control applications.

Three-position solenoid

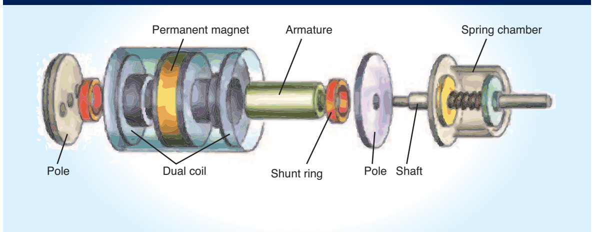

Figure 8: Most three-position latching solenoids have an armature that can be electromagnetically switched to any of three positions, but is held in the center position by two opposing springs even if power is lost. The design here uses only one spring, which expands against a hard stop to center the armature and compresses when the armature moves in either direction – for tighter tolerance on the solenoid's center position.

Design Objective: Targeted force and stroke

Following are customizable elements that can be used to optimize solenoid force and stroke movement:

Armature shape	Flux pole	(If installed) properly sized springs	Proper duty cycle

Solenoid force is a function of the field strength, which varies with armature geometry, position, and coil current. When the armature is open (maximum airgap), it outputs the least amount of force; when it's closed (minimum airgap), it outputs maximum force. Therefore, a solenoid's rated force should match the load.

Design Objective: Positioning

Solenoids can be designed to push, pull, or both push and pull. The application's mechanical setup and motion requirements dictate which design is most appropriate. Solenoids capable of both pushing and pulling can be used for either discrete positioning or infinite positioning. The latter makes use of proportional controls. The following elements can be used to customize a solenoid for positioning applications:

Electromagnetic arrangement	Springs	Hard stops

Three-position solenoids integrate one or more springs and hard stops to output three discrete positions — eliminating the need for multiple solenoids.

Design Objective: Power consumption and efficiency

Power can be reduced by using latching technology or peak-and-hold drive circuits.

Following are customizable elements that can be used to optimize solenoid efficiency:

Latching technologies	Copper wire coil	Specialized control circuitry	Peak-and-hold where appropriate

As noted, latching solenoids, in particular, are designed to be green — by consuming no power, producing no heat, and generating no electrical noise while holding in either the on or off position. Both permanent magnet and residual magnetism latching solenoids are suitable for high-speed actuation and long open or close times. Certain drive circuits also improve efficiency:

Design Objective: Heat dissipation

Following are customizable subcomponents that can increase solenoid heat resistance:

Copper wire coil	Insulation of magnetic wire in coil	Potting of the coil	Proper sizing for application at hand

Solenoids produce heat when powered. As power or voltage is applied to the solenoid, its temperature will rise, causing the resistance to increase and reducing the current to the solenoid, which reduces the force output. Anything that reduces current amplitude or frequency reduces heat. The goal is to dissipate as much heat as possible to reduce the coil's temperature.

Design Objective: Package-size constraints

Following are customizable elements that can make a solenoid design more compact:

Precision-wound coil	Copper wire coil	Specialized control circuitry

Design Objective: Environmental protection

Following are customizable elements that increase solenoid durability:

Tubular or cylindrical	Encapsulating coils	Stainless armature material where required

Design Objective: Fast response time

Force, stroke, power, magnetic design, and material are factors in high-speed solenoid functionality:

$$\left.\begin{array}{l}\textbf{Force (higher)}\\ \textbf{Stroke (lower)}\\ \textbf{Mass (lower)}\\ \textbf{Voltage (higher)}\end{array}\right\} = \textbf{Faster response time}$$

The higher the voltage, the faster the solenoid's electrical response will be. When designing the magnetic response of the solenoid, a combination of the magnetic design and material selected must be considered. A combination of both the electrical response and the magnetic response affects the solenoid's overall response time.

Make contact

Every solenoid designed by **TLX Technologies** begins with an analysis of the application so that the end product best suits the requirements. Every detail of the solenoid construction, material selection, and operation is optimized, including magnetics — customized for maximum efficiency and minimized footprint and cost.

The strength of **TLX Technologies** is in the company's progressive technology and ability to deliver solutions that exceed expectations. The **TLX technical** team has almost 150 years of combined experience in designing and developing solenoid solutions for a wide variety of applications. Learn about the advantages of working with **TLX Technologies** at **www.tlxtech.com/about/tlx-advantage.**

To discuss your project with our technical team, please contact us:
Phone: 262-970-8660
Email: engineering@tlxtech.com
Website: www.tlxtech.com

N27 W23727 Paul Road, Pewaukee, WI 53072 USA | www.tlxtech.com
sales@tlxtech.com | P: 262.970.8660 | F: 262.970.8665