

# DC Precharge Circuit for Hybrid and Electric Vehicles

## 1. Introduction

High-voltage systems in hybrid and electric vehicles contain significant downstream capacitance, typically in motor inverters and DC link assemblies. When battery voltage is suddenly applied to an uncharged capacitive load, extremely large transient currents can occur. These current spikes may reach thousands of amps and can severely damage components. Specifically, by welding contactor contacts closed.

A precharge circuit is used to limit this initial inrush current and bring the downstream voltage close to battery voltage before the main contactors close. Properly designed precharge systems improve reliability, extend contactor life, prevent nuisance fuse trips, and protect sensitive electronics.

## 2. Why Precharge Is Required

### 2.1 The Real Cause of Contactor Welding

Although short circuits and vibration events can weld contactors, the most common cause is uncontrolled inrush current into capacitive loads during contactor closing.

A frequent customer complaint is that the contactor welded even though they did not apply high currents. Welding almost always occurs during closing due to current levels far in excess to nominal amounts. The failure is discovered when the contactor is commanded to open and cannot.

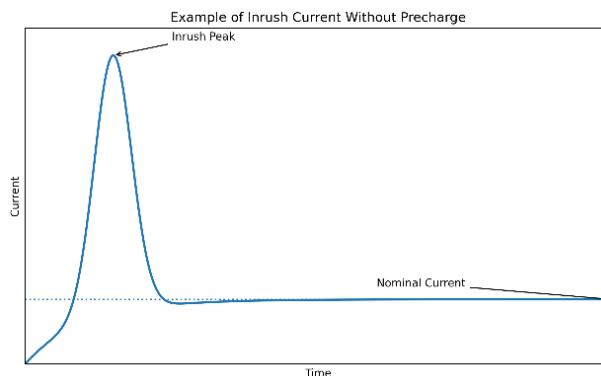


Figure 1: Relation of inrush current magnitude and duration to nominal.

Without precharge:

- Capacitors appear as a near short circuit at  $t = 0$ .
- Very high instantaneous current flows.
- Contact bounce creates arcing.
- Localized heating causes fusion of contact material.

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### 2.2 Additional Benefits of Precharge

A properly implemented precharge circuit:

- Reduces stress on contactors
- Protects battery cells from surge currents
- Prevents nuisance fuse or breaker trips
- Helps detect downstream faults

### 3. Understanding Inrush in Different Load Types

Contactors switching behavior depends on load characteristics:

#### 3.1 Resistive Loads

Pure resistive loads limit current inherently. No significant inrush occurs.

#### 3.2 Inductive Loads

Inductors resist changes in current. Closing is generally manageable.

Opening under load is challenging because current persists, increasing arc energy.

#### 3.3 Capacitive Loads (Primary Concern in EVs)

Capacitors resist changes in voltage. When energized:

- Initial current spike is very high
- Current decays exponentially
- Voltage rises gradually

This is the dominant case in EV traction systems.

### 4. The Physics of Capacitive Inrush

When voltage is applied to an uncharged capacitor:

- Initial current =  $V / R$  (limited only by circuit resistance)
- Voltage across the capacitor increases exponentially
- Current decays exponentially

Without precharge, current duration is extremely short (50–100 microseconds) but very high in magnitude and requires high-bandwidth measurement equipment to capture accurately.

Because the battery voltage and system capacitance are typically fixed, the only controllable design parameter is time. A resistor inserted in series slows the charging process and limits current.

### 5. Typical EV Precharge Circuit Architecture

A standard traction battery disconnect includes:

- Main positive contactor
- Main negative contactor
- Precharge contactor
- Series precharge resistor

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The precharge branch (resistor + smaller contactor) is placed in parallel with the main positive contactor.

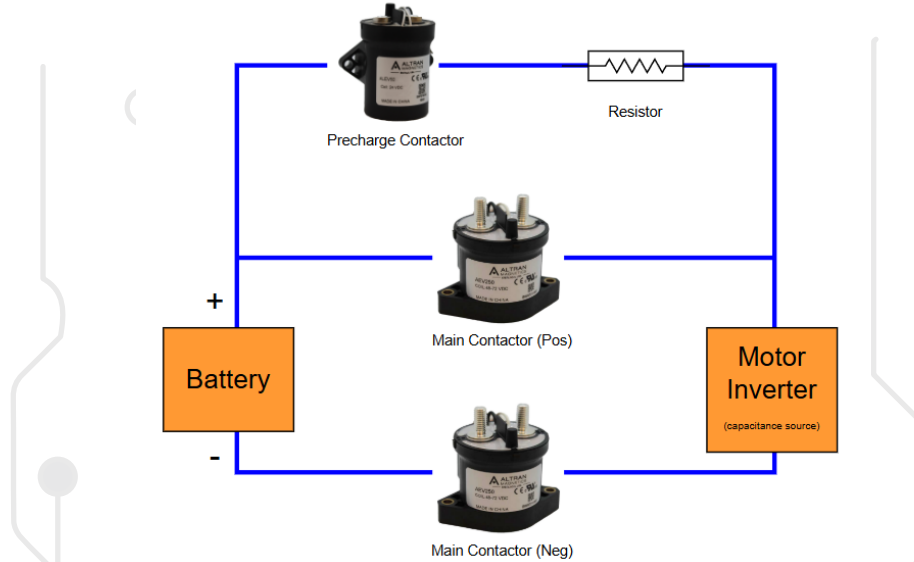


Figure 2: Standard precharge circuit components.

Sequence of a standard precharge circuit:

1. Close main contactor negative
2. Close precharge contactor
3. Allow capacitors to charge through resistor
4. Close main contactor positive
5. Open precharge contactor

This ensures the main contactor closes with minimal voltage differential.

### 6. RC Circuit Fundamentals

When a resistor is placed in series with a capacitor, the charging follows exponential behavior.

#### 6.1 Time Constant

$$\tau = R * C$$

Where:

$R$  = resistance (Ohms)

$C$  = capacitance (Farads)

After one time constant:

Capacitor reaches 63.2% of supply voltage

Current drops to 36.7% of initial value

After 5 time constants:

Capacitor reaches ~99.3% of supply voltage

Considered fully charged for practical design

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Thus, precharge time is typically designed as:

$$T_{precharge} = 5\tau$$

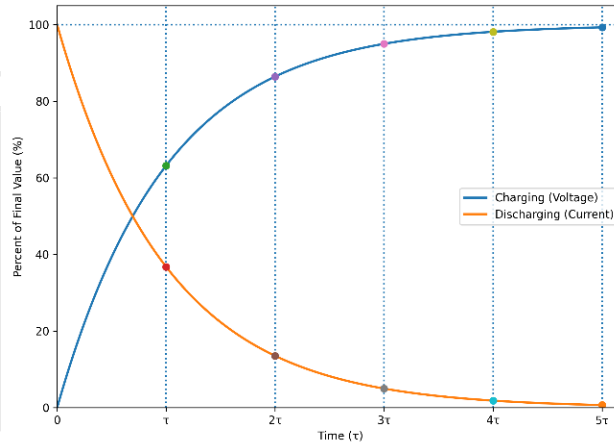


Figure 3: RC circuit behavior.

## 7. Selecting the Precharge Resistor

### 7.1 Determining Resistance

If desired precharge time is known:

$$R = \frac{T_{precharge}/5}{C}$$

Example:

- Battery voltage: 900 V
- Capacitance: 8 mF (0.008 F)
- Desired precharge time: 1 s

$$\tau = 0.2s$$

Initial current:

$$R = \frac{0.2}{0.008} = 25\Omega$$

$$I_0 = \frac{900}{25} = 36A$$

Instead of hundreds or thousands of amps, peak inrush becomes only 36A.

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**8. Energy and Power Considerations**

**8.1 Energy Stored in Capacitor**

For sufficiently long precharge ( $\geq 3\tau$ ):

$$U = \frac{1}{2} CV^2$$

Using the example:

$$U = 0.5 \times 0.008 \times 900^2$$

$$U = 3240J$$

The resistor must dissipate approximately this same energy during precharge.

**8.2 Instantaneous and Average Power**

Instantaneous power:

$$P(t) = I(t)^2 R$$

Peak power occurs at  $t = 0$ :

$$P_{peak} = I_0^2 R$$

In example:

$$P_{peak} = 36^2 \times 25 = 32,400W$$

This peak lasts only briefly.

Average power over precharge:

$$P_{avg} = \frac{U}{T}$$

$$P_{avg} = \frac{3240}{1} = 3240W$$

Resistor selection must account for:

- Peak pulse capability
- Energy rating
- Thermal recovery
- Repetitive cycling behavior

Manufacturers often specify short-duration overload ratings (e.g., 5x rated power for 5 seconds).

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### 9. Practical Resistor Selection Guidelines

- *Must be rated for full battery voltage*
- *Must tolerate calculated energy*
- *Must handle peak pulse power*
- *Consider temperature extremes*
- *Consider repetition rate*
- *Validate with manufacturer when possible*

*Heat-sinkable aluminum-bodied resistors are common in EV precharge applications.*

*Because off-the-shelf values may not match calculations exactly, re-run timing and power analysis when choosing nearest available resistance.*

### 10. System Validation and Testing

*Design margin should account for:*

- *Component tolerances*
- *Minimum/maximum temperature*
- *Voltage variation*
- *Capacitance tolerance*
- *Repeated cycling*

### 11. Failure Modes

*Common causes of precharge failure:*

- *Attempting precharge while loads are active*
- *Excessive repeated cycling (thermal overload due to insufficient cool down time)*

*For high robustness, a resistor capable of repeated cycling without cooldown may be preferred, though at higher cost.*

### 12. Summary and Design Philosophy

*A properly designed precharge circuit:*

- *Reduces voltage differential before main contact closure*
- *Prevents contact welding*
- *Protects batteries and electronics*
- *Improves reliability*
- *Enables fault detection*
- *Reduces nuisance protection trips*

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The key design levers are:

1. Precharge resistance value
2. Precharge time
3. Energy and thermal rating of resistor
4. Peak power tolerance

In high-voltage EV systems precharge is a fundamental protection strategy.

[Click here to access full HVDC Selection Chart](#) 

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