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## NANDIGHOSH ROADX MOTORS PVT LTD

**PROJECT REPORT**

### **Over-/Under-Voltage Protection**

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## Abstract

This report presents a comprehensive study of over- and under-voltage protection strategies for electric vehicles (EVs) and their charging infrastructure, with direct applicability to ROADX Motor's engineering and manufacturing operations. Over- and under-voltage events—whether transient surges caused by lightning, switching operations, and inductive load interruptions, or sustained deviations due to grid instability, load unbalance, or component faults—pose significant risks to EV power electronics, traction inverters, on-board chargers, and battery packs [1], [2]. These conditions can result in accelerated insulation breakdown, semiconductor failure, excessive heat dissipation, data corruption in control systems, and reduced overall system lifespan.

The report synthesizes theoretical principles of voltage disturbance formation, discusses internationally recognized standards and compliance requirements (such as IEC 60364-7-722 for EV charging installations), and reviews device-level protective technologies including surge protective devices (SPDs), transient voltage suppression (TVS) diodes, metal-oxide varistors (MOVs), crowbar circuits, precharge resistor networks, undervoltage lockout (UVLO) circuits, and battery management system (BMS) cutoff thresholds [3]–[5]. Circuit-level topologies for coordinated protection between grid-side equipment, EVSE (Electric Vehicle Supply Equipment), and on-board systems are analyzed, emphasizing the need for layered defense mechanisms that address both short-duration spikes and long-duration voltage anomalies [6], [7].

Special attention is given to the unique challenges in EV architectures, such as DC-link overvoltage following abrupt battery disconnection [8], regenerative braking surges, and under-voltage sag during high-load transients. Case studies from peer-reviewed research and industry practice illustrate mitigation techniques, such as coordinated operation of TVS and MOV devices, staged SPD arrangements, and the integration of precharge systems to avoid inrush current damage. The analysis culminates in a set of engineering recommendations for ROADX Motor, focused on improving safety, reliability, and compliance with applicable EV electrical standards.

By combining theoretical insights, empirical data, and industry-accepted best practices, this report provides a solid reference framework for engineers tasked with designing robust over-/under-voltage protection schemes in modern EV systems [9], [10].

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## 1. Introduction

The rapid advancement of electric vehicle (EV) technology has brought significant attention to the reliability and safety of power electronic systems. Among the critical protection mechanisms implemented in EVs, **over-voltage and under-voltage protection** play a vital role in ensuring operational stability, preventing component damage, and maintaining passenger safety. Over-voltage conditions can occur due to regenerative braking events, sudden load rejection, or faults in the charging infrastructure, while under-voltage events may result from prolonged high-load operation, degraded battery capacity, or sudden surge in demand [10].

Voltage deviations—either above (over-voltage) or below (under-voltage) the nominal design level—pose a significant hazard for electric vehicle power electronics, battery packs and charging infrastructure. Over-voltage events can stress insulation, increase leakage and accelerate aging or immediate component failure; under-voltage (including 'brownouts') can lead to malfunction, stalled power conversion, or unsafe operating conditions for motor controllers and auxiliary electronics. In EV charging installations transient surges (from lightning or switching) and steady-state deviations (grid faults or long sagging lines) are both important failure modes to address [1][4].

In EVs such as those developed at **ROADX Motor**, battery packs and motor controllers operate within strict voltage ranges to optimize performance and lifespan. Deviations from these limits can cause irreversible harm to lithium-ion battery cells, damage to inverters, or reduced efficiency of the drivetrain [11]. Therefore, precise voltage monitoring and fast protective responses are indispensable.

The **over-voltage protection (OVP)** system detects voltage exceeding the maximum permissible threshold and initiates corrective actions, such as load disconnection, absorption through braking choppers, or controlled shutdown. Similarly, **under-voltage protection (UVP)** prevents excessive battery discharge and associated risks, including loss of propulsion or irreversible battery degradation [12]. In high-performance EV systems, these protections are often integrated into the Battery Management System (BMS) and Power Electronics Control Unit (PECU), providing real-time safeguards.

Given the high energy density and chemical sensitivity of lithium-ion batteries, ensuring effective over/under-voltage protection is not only a matter of performance but also of safety and compliance with international EV standards such as IEC 61851 and ISO 26262 [13]. This report presents a comprehensive study of over/under-voltage protection principles, their relevance in EV applications, and specific approaches adopted in modern systems, with a focus on potential implementations for ROADX Motor's product line.

## 2. Objectives

The purpose of this internship report is to consolidate theoretical knowledge, industry practice, and engineering design principles related to over- and under-voltage protection in electric vehicle (EV) systems. This work is intended to support ROADX Motor's product development efforts by establishing a technical foundation and actionable recommendations for the integration of robust voltage protection strategies into future EV platforms. The specific objectives are:

- **To describe the mechanisms that create over- and under-voltage events in EV systems.** This includes transient over-voltage phenomena caused by lightning strikes, switching surges, regenerative braking, and sudden load rejection 111–333, as well as under-voltage conditions arising from grid instability, excessive load demand, or deep battery discharge 999–121212.
- **To review established and emerging protection techniques from literature and industry practice.** This encompasses surge protective devices (SPDs), transient voltage suppression (TVS) diodes, metal-oxide varistors (MOVs), crowbar circuits, precharge resistor networks, battery management undervoltage lockouts (UVLO), and coordinated multi-layer protection strategies 111, 555, 666, 999.
- **To recommend practical, testable protection designs and procedures appropriate to ROADX Motor's EV platforms.** Recommendations are based on compliance with standards such as IEC 60364-7-722 444 and IEC 61851-1 131313, real-world case studies, and simulation data 222, 777, 888.
- **To provide a clear set of references and implementation guidance** so that over/under-voltage protection measures can be systematically integrated into future design cycles, prototype builds, and validation plans, ensuring safety, reliability, and regulatory compliance.

By achieving these objectives, this report aims to serve as both a technical reference and a practical engineering guide for ROADX Motor's current and upcoming EV projects.

### 3. Background and Effects of Voltage Deviations

Overvoltage and undervoltage conditions are critical power quality issues that can severely impact the performance, safety, and longevity of electrical and electronic systems, particularly in Electric Vehicles (EVs). These phenomena are typically associated with abnormalities in the power supply or faults within the system that cause the voltage level to rise above or fall below the nominal operating range [1]. In the context of EVs, these conditions can arise from various sources, such as sudden load changes, regenerative braking surges, or faults in the charging infrastructure [2].

#### 3.1 Overvoltage

Overvoltage occurs when the supply voltage exceeds the upper design limit of the system. This can be classified into two types:

1. **Transient Overvoltage** – short-duration surges often caused by switching operations, lightning strikes, or rapid changes in load [3].
2. **Sustained Overvoltage** – longer-duration voltage rise, typically resulting from faults in voltage regulation equipment or incorrect control signals [4].

The effects of overvoltage in EV systems include insulation breakdown, overheating of motor windings, premature capacitor failure in inverters, and reduced battery life due to excessive charging stress [5]. Prolonged exposure to high voltage levels can also damage sensitive control electronics and sensors, leading to unsafe vehicle operation [6].

#### 3.2 Undervoltage

Undervoltage refers to a condition where the voltage drops below the required minimum threshold. Common causes include excessive load demand, poor grid supply quality, high impedance connections, or faults in the onboard power distribution system [7]. In EV applications, undervoltage can impair motor torque generation, trigger unintended shutdown of auxiliary systems, and cause power electronics to operate outside their safe operating area [8].

Additionally, undervoltage can lead to increased current draw in the system, which may result in overheating of conductors, higher energy losses, and reduced overall efficiency [9]. This is particularly critical during high-power demands, such as vehicle acceleration or climbing steep gradients.

### 3.3 Importance of Voltage Protection in EVs

Given the high reliance on power electronics and battery management systems in EVs, maintaining voltage stability is essential to ensure optimal performance, safety, and component longevity [10]. Over/under voltage protection mechanisms safeguard against costly damages, minimize downtime, and enhance the safety of passengers and operators [11]. Moreover, with the increasing penetration of fast-charging infrastructure, these protection systems must be designed to handle rapid changes in voltage levels while ensuring compliance with international safety standards such as IEC 61851 and ISO 6469 [12].

## 4. Design and Implementation

The design of the Over/Under Voltage Protection Circuit for the ROADX project aims to ensure that electrical appliances are safeguarded against fluctuations in the supply voltage. The implementation process involves both the **hardware circuitry** and the **control logic** required to detect and respond to abnormal voltage conditions.

### 4.1 Design Objectives

The primary objectives for the circuit include:

- **Accurate voltage sensing:** The system must measure the input voltage with minimal error to detect deviations beyond the safe range.
- **Reliable switching:** The load should be promptly disconnected in unsafe voltage conditions and reconnected when normal conditions resume.
- **Adjustable limits:** The voltage threshold levels for both overvoltage and undervoltage conditions should be configurable.
- **Fail-safe operation:** The system should default to a safe state (load disconnected) if a component failure occurs [1].

### 4.2 Circuit Components

The hardware design integrates the following main components:

- **Step-down Transformer:** Used to scale the high AC mains voltage to a lower AC voltage suitable for measurement.
- **Rectifier and Filter:** Converts the AC signal to DC and smooths fluctuations for precise sensing.

- **Voltage Divider Network:** Scales the DC voltage to a level acceptable for the microcontroller's ADC input.
- **Microcontroller (e.g., Arduino UNO):** Reads the scaled voltage via the ADC, processes it, and triggers the relay module when thresholds are crossed.
- **Relay Module:** Controls the connection between the power source and the load, providing electrical isolation.
- **Display Unit:** Shows the real-time voltage readings and status of the protection system.

#### 4.3 Working Principle

The system works as follows:

1. The step-down transformer reduces the mains voltage to a safer level.
2. The rectifier and capacitor filter produce a stable DC signal proportional to the AC mains voltage.
3. The microcontroller continuously reads this voltage via its ADC input and compares it with predefined upper and lower thresholds.
4. If the voltage exceeds the upper limit or falls below the lower limit, the microcontroller deactivates the relay, cutting off the load.
5. When the voltage returns to the normal range for a predefined delay time, the relay is reactivated, restoring the load connection [2].

#### 4.4 Implementation Steps

The design was implemented through the following steps:

- **Component Selection:** Chosen based on voltage rating, response time, and durability.
- **Circuit Simulation:** Conducted in software such as Proteus to verify functionality before hardware assembly.
- **PCB Layout Design:** Ensured minimal interference and efficient routing.
- **Assembly and Testing:** Components were soldered onto the PCB, and the circuit was tested under controlled voltage variations.
- **Calibration:** Thresholds were fine-tuned using a variable power supply to ensure accurate triggering points [3].

#### 4.5 Safety Considerations

Since the circuit interacts with mains voltage, several safety measures were implemented:

- Electrical isolation using a relay and optocoupler.
- Proper insulation and enclosures for high-voltage parts.

- Use of fuses to protect against overcurrent conditions.

## 5. Protection Devices and Principles

Protection devices are integral components of electrical power systems, designed to safeguard equipment, maintain system stability, and ensure the safety of personnel. In the context of the Y-Bus matrix and power system analysis, understanding protection devices is essential for modeling fault conditions, determining system behavior under contingencies, and designing appropriate response mechanisms. Protection systems typically consist of **sensing elements**, **decision-making units**, and **actuating devices**.

The fundamental principle of protection is to detect abnormal operating conditions—such as overcurrent, overvoltage, underfrequency, or unbalanced power flow—and to isolate the affected portion of the network before the fault propagates and causes further damage [12].

### 5.1 Types of Protection Devices

#### 1. Relays

Protective relays are intelligent devices that continuously monitor system parameters and initiate tripping commands to circuit breakers when thresholds are exceeded. Modern digital relays employ microprocessor-based architectures, allowing for multifunctional capabilities, self-testing, and integration with SCADA systems [13]. Relays can be classified into:

- **Overcurrent relays:** Trip when current exceeds a preset value.
- **Distance relays:** Operate based on the impedance between relay location and fault point.
- **Differential relays:** Compare current entering and leaving a protected zone to detect discrepancies.

#### 2. Circuit Breakers

Circuit breakers are mechanical devices capable of making and breaking currents under both normal and fault conditions. In high-voltage networks, **SF<sub>6</sub> circuit breakers** are widely used due to their superior dielectric strength and arc-quenching capability [14].

#### 3. Fuses

Fuses are passive protection devices that melt under excessive current, providing simple and cost-effective protection for low-voltage circuits. While they offer fast response, their inability to be reset limits their application in modern high-voltage systems [15].

#### 4. Surge Arresters

Surge arresters protect electrical equipment from transient overvoltages caused by lightning strikes or switching surges. They operate by providing a low-impedance path for surge currents and then returning to a high-impedance state under normal operation [16].

### 5.2 Principles of Power System Protection

The guiding principles of electrical protection ensure that protective systems operate effectively, selectively, and reliably:

- **Selectivity:** Only the faulty section of the system should be disconnected, leaving the rest of the network in operation [17].
- **Speed:** Fault clearance should be rapid to minimize damage to equipment and reduce system instability risks.
- **Sensitivity:** Protective devices must detect even low-magnitude faults that may cause long-term degradation.
- **Reliability:** The protection system must operate correctly when required and remain inactive under normal conditions.
- **Simplicity and Economy:** The protection scheme should be straightforward in design and cost-effective without compromising effectiveness.

### 5.3 Role in Y-Bus Analysis

In Y-Bus modeling, protection devices indirectly influence the network representation. For example:

- **Circuit breaker operation** during a fault can be simulated by modifying the corresponding bus admittance matrix to reflect the disconnection of a branch.
- **Relay coordination studies** use Y-Bus-based short-circuit calculations to determine pickup settings and time delays.
- **Fault location estimation** in transmission lines often involves impedance calculations derived from Y-Bus data [18].

Thus, protection devices not only serve a practical safeguarding role but also play a critical part in analytical modeling and contingency planning for power systems.

## 6. Protection Architectures for EVs and Chargers

The protection architecture in Electric Vehicles (EVs) and their charging systems is designed to safeguard critical components, ensure passenger safety, and maintain operational reliability. A well-designed architecture integrates multiple protection layers—mechanical, electrical, and electronic—to address a variety of fault conditions.

A typical EV protection system consists of:

- **High-Voltage (HV) Circuit Protection:** Fuses, contactors, and circuit breakers prevent overcurrent conditions that could damage the traction battery or power electronics [1].
- **Isolation Monitoring Devices (IMDs):** These continuously monitor the insulation resistance between the HV system and the vehicle chassis, preventing shock hazards [2].

- **Ground Fault Protection:** Residual Current Devices (RCDs) in EV supply equipment (EVSE) detect leakage currents and disconnect the supply [3].
- **Thermal Protection:** Temperature sensors and thermal cut-offs protect batteries, motors, and inverters from overheating [4].
- **Surge and Transient Protection:** Surge Protective Devices (SPDs) safeguard the onboard charger and charging station electronics from voltage spikes [5].

In charging systems, both **AC Level 2** and **DC fast charging** architectures require:

1. **Input-side overvoltage protection** using MOVs (Metal Oxide Varistors) and transient suppressors [6].
2. **Output-side battery protection** with current limiting and reverse-polarity safeguards [7].
3. **Communication protection** (CAN, PLC) with signal isolators and TVS diodes to prevent data corruption [8].

A layered architecture ensures that no single point of failure compromises overall safety. For example, even if a contactor welds closed, a fuse still acts as a fail-safe [9].

## 7. Design Recommendations for ROADX Motor

For the **ROADX Motor** used in high-performance EV applications, protection design should consider both operational safety and long-term reliability. The following recommendations are derived from industry standards and field experience:

### 1. Overcurrent and Short-Circuit Protection

- Use **fast-acting fuses** on the HV DC link between the battery and inverter to protect motor windings and control electronics [10].
- Incorporate electronic current limiting in the inverter firmware to prevent torque spikes during faults [11].

### 2. Thermal Management and Overtemperature Protection

- Integrate **PT100/PT1000 temperature sensors** in stator windings and bearings [12].
- Implement **active derating algorithms** that reduce torque output when temperatures approach safe limits [13].

### 3. Insulation and Ground Fault Protection

- Perform routine **partial discharge tests** to ensure insulation health [14].
- Include **IMD integration** for real-time isolation monitoring [15].

### 4. Vibration and Mechanical Stress Monitoring

- Install accelerometers for **vibration diagnostics** to detect bearing wear or rotor imbalance [16].
- Apply predictive maintenance analytics based on collected data [17].

## 5. Environmental Sealing and IP Rating

- For harsh environments, ensure **IP67 or higher** enclosure rating to prevent water and dust ingress [18].

By following these recommendations, the ROADX Motor can achieve **enhanced safety, extended lifespan, and compliance with international EV protection standards** [19].

## 8. Implementation & Test Methodology

The implementation of over- and under-voltage protection systems at ROADX Motor follows a rigorous process to ensure reliability, safety, and compliance with industry standards. This section outlines the steps taken from prototype development to validation testing.

### 8.1 Implementation Approach

The protection circuitry is designed to integrate seamlessly with existing EV control and battery management systems. The hardware implementation includes surge protective devices (SPDs), undervoltage lockout (UVLO) circuits, and precharge mechanisms to manage voltage transients during startup and shutdown phases [1], [5], [6]. Microcontroller-based monitoring allows real-time voltage measurement and fast relay activation to disconnect loads when unsafe conditions are detected [3].

### 8.2 Testing Procedures

Testing follows internationally recognized standards such as IEC 60364-7-722 and IEC 61851 to validate the effectiveness of voltage protection systems under various conditions [4], [13]:

- **Functional Testing:** Verifies that overvoltage and undervoltage thresholds trigger the protection system accurately. Tests include ramping voltage up and down to trigger the system responses and ensure no false trips occur under normal conditions.
- **Surge Testing:** Applies standardized transient voltage surges (e.g., IEC 61000-4-5) to evaluate SPD response times and energy absorption capacity [5].
- **Endurance Testing:** Simulates repeated over/under voltage events to assess long-term reliability and component degradation.
- **Integration Testing:** Confirms compatibility with the overall EV system, including communication protocols and failsafe responses during fault conditions.

### 8.3 Data Acquisition and Analysis

Voltage and current waveforms are recorded during testing using high-precision oscilloscopes and data loggers. This data aids in refining protection thresholds and optimizing component selection for the ROADX Motor EV platforms [8], [9].

## 9. Case Studies & Literature Findings

The following case studies and literature findings provide insights into practical challenges and solutions for over-/under-voltage protection in EV systems.

### 9.1 Case Study: DC-Link Overvoltage in EV Inverters

Chandran et al. [3] investigated overvoltage transients during freewheeling states in EV inverters, demonstrating that inadequate protection can lead to capacitor damage and inverter failure. Their analytical models suggest that combining crowbar circuits with precharge resistors effectively mitigates such events, a strategy applicable to ROADX Motor designs.

### 9.2 Case Study: Surge Protection in EV Charging Infrastructure

The white paper by Raycap [1] outlines the necessity of multilayer surge protective devices in EV charging stations to protect against lightning-induced surges and switching transients. Implementing MOVs and coordinated SPDs at multiple points in the charging path reduces equipment damage and downtime.

### 9.3 Literature Review: Battery Management System Protections

Recent reviews [9] highlight the role of undervoltage lockout (UVLO) functions and state-of-charge monitoring algorithms to prevent deep discharge and battery degradation. Integrating these protective features within the BMS enhances safety and extends battery life, aligning with ROADX Motor's performance goals.

### 9.4 Emerging Trends

Advanced protection architectures leveraging real-time data analytics and adaptive thresholding are gaining traction [7], enabling dynamic response to varying operational conditions. This aligns with industry trends emphasizing smart protection systems in EVs.

## 10. Conclusion & Future Work

Overvoltage and undervoltage protection are critical components in ensuring the safety, reliability, and longevity of electric vehicle (EV) systems. This report has provided a comprehensive overview of the mechanisms leading to voltage abnormalities, the protective devices and architectures commonly employed, and design recommendations tailored specifically for ROADX Motor's EV platforms.

The integration of multilayer protection strategies—including surge protective devices, precharge circuits, undervoltage lockouts, and battery management system safeguards—forms the foundation for effective voltage regulation and fault mitigation in EVs and charging infrastructure [1], [3], [5], [9]. Implementing these protections in a coordinated manner minimizes the risk of component failure, enhances user safety, and supports compliance with international standards such as IEC 60364-7-722 and IEC 61851 [4], [13].

Testing methodologies aligned with industry standards validate the robustness of protection designs and inform ongoing improvements. Case studies and literature reinforce the importance of adaptive and intelligent protection systems capable of handling dynamic operating conditions and emerging challenges in EV technology [7], [8].

Looking forward, future work should focus on the integration of advanced monitoring techniques, including real-time diagnostics and predictive maintenance enabled by machine learning and IoT technologies. These approaches promise to enhance the responsiveness and adaptability of voltage protection systems, thereby further improving EV safety and performance [7].

Additionally, as battery chemistries and power electronics evolve, continuous updates to protection algorithms and hardware will be necessary to address new failure modes and regulatory requirements. ROADX Motor is well-positioned to lead in these innovations by incorporating flexible, scalable protection architectures in its next generation of electric vehicles.

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