配网设备故障分析及基于遥测数据的实时检测方案

1. 引言

在现代基础设施中，可靠的电力分配发挥着至关重要的作用。随着配网设备的日益复杂，及时准确地检测故障对于确保系统稳定性、最大限度地减少停机时间以及防止设备损坏变得越来越重要。通过对来自馈线终端单元 (FTU) 的遥测数据进行实时分析，可以为配电网络的健康状况和运行状态提供宝贵的见解。本报告旨在分析配网设备中特定故障类型的电气特性，并将这些特性转化为 TimescaleDB 数据仓库的 SQL 查询，以实现故障的自动检测和分类。报告重点关注五种关键故障类别：短路故障、接地故障、失压故障、过载故障和断路故障，并深入探讨它们的二级分类。通过建立故障表现与遥测数据之间的联系，本报告旨在为配网设备的实时故障监测提供一个可行的框架。

2. 目标故障类型及其二级分类概述

本节旨在列出用户查询中指定的五种主要故障类型下的二级分类。由于无法访问提供的外部链接 https://omhost.net/misc2025/ftu-fault-types，以下二级分类是基于对配电系统故障的一般理解和可用的研究片段进行的合理假设。在实际应用中，应使用从该链接获得的实际二级分类替换这些占位符。

- 短路故障 **(Short Circuit Faults):**
  - 三相短路
  - 相间短路
  - 单相接地短路
  - 电弧短路
  - 金属性短路
- 接地故障 **(Ground Faults):**
  - 直接接地故障
  - 高阻抗接地故障
  - 间歇性接地故障
  - 带电弧的接地故障
  - 多点接地故障
- 失压故障 **(Loss of Voltage Faults):**
  - 完全失压
  - 相间失压
  - 瞬时电压跌落
  - 持续欠压
  - 电压不平衡
- 过载故障 **(Overload Faults):**
  - 轻微过载
  - 严重过载

    - 短期过载
    - 长期过载
    - 电机启动过载
- 断路故障 **(Open Circuit Faults):**
    - 单相断路
    - 两相断路
    - 三相断路
    - 间歇性断路
    - 中性线断路

二级分类的细致程度对于精确的故障诊断和有针对性的响应策略至关重要。理解每个主要类别中的细微差别可以实现更有效的故障排除和预防性维护。例如，区分金属性短路和电弧短路非常重要，因为它们具有不同的特性和潜在后果 [1]。金属性故障通常涉及直接的低阻抗连接，导致高故障电流和保护装置的快速动作。另一方面，电弧故障可能具有更高的阻抗，并且更难以检测，如果不及时清除，可能会导致火灾或设备损坏。类似地，理解瞬时电压跌落和持续欠压之间的区别对于确定适当的措施至关重要 [3]。

3. 故障表现分析与 **SQL** 查询设计

本节详细描述了五种主要故障类型及其假设的二级分类。对于每个二级分类，将描述在配网设备遥测数据中观察到的典型电气特性或表现。这将涉及分析电流、电压、零序电流以及其他相关参数的变化。然后，将根据假设的遥测数据仓库模式设计相应的 TimescaleDB SQL 查询，以检测这些故障情况。这些查询将在适当的情况下利用 TimescaleDB 的时序函数。

- **3.1.** 短路故障 **(Short Circuit Faults)**
    - **3.1.1.** 三相短路
        - **表现：**所有三相电流突然显著增加，同时所有三相电压明显下降。保护装置（例如，断路器、熔断器）通常会快速跳闸 [1]。短路故障通常具有较高的故障电流 [8]。
        - **SQL** 查询示例：

```SQL
SELECT time, device_id,
    CASE
        WHEN current_phase_a > threshold_high_current
            AND current_phase_b > threshold_high_current
            AND current_phase_c > threshold_high_current
            AND voltage_phase_a < threshold_low_voltage
            AND voltage_phase_b < threshold_low_voltage
            AND voltage_phase_c < threshold_low_voltage
```

```
        THEN 'Three-Phase Short Circuit'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND (current_phase_a > threshold_high_current
    OR current_phase_b > threshold_high_current
    OR current_phase_c > threshold_high_current)
  AND (voltage_phase_a < threshold_low_voltage
    OR voltage_phase_b < threshold_low_voltage
    OR voltage_phase_c < threshold_low_voltage);
```

说明：此查询检查最近 5 分钟内所有三相电流是否同时激增且电压是否下降。threshold_high_current 和 threshold_low_voltage 需要根据设备的正常运行参数来定义。电流增加和电压下降的速度和幅度有助于区分不同类型的短路和其他故障情况。使用 TimescaleDB 的窗口函数（例如 LAG 或 LEAD）分析这些参数的变化率可以提供更复杂的检测逻辑 [9]。例如，在短时间内电流的快速增加和电压的急剧下降是严重短路的有力指标。可以使用 LAG 将当前时间戳的电流和电压值与前一个时间戳（例如，几秒钟前）的值进行比较。如果差值超过某个阈值，则可以触发短路警报。

- **3.1.2.** 相间短路
  - **表现：**其中两相电流显著增加，同时这两相之间的电压下降。未受影响的相的电流可能保持相对正常 [10]。
  - **SQL** 查询示例：

```
SQL
SELECT time, device_id,
    CASE
        WHEN (current_phase_a > threshold_high_current AND
current_phase_b > threshold_high_current AND voltage_phase_ab <
threshold_low_voltage)
            OR (current_phase_b > threshold_high_current AND
current_phase_c > threshold_high_current AND voltage_phase_bc <
threshold_low_voltage)
            OR (current_phase_c > threshold_high_current AND
current_phase_a > threshold_high_current AND voltage_phase_ca <
threshold_low_voltage)
        THEN 'Phase-to-Phase Short Circuit'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
```

```
WHERE time > NOW() - INTERVAL '5 minutes'
  AND ((current_phase_a > threshold_high_current AND current_phase_b > threshold_high_current AND voltage_phase_ab < threshold_low_voltage)
       OR (current_phase_b > threshold_high_current AND current_phase_c > threshold_high_current AND voltage_phase_bc < threshold_low_voltage)
       OR (current_phase_c > threshold_high_current AND current_phase_a > threshold_high_current AND voltage_phase_ca < threshold_low_voltage));
```

说明：除了相地电压，监测线间电压（voltage_phase_ab、voltage_phase_bc、voltage_phase_ca）可以提供关于短路类型的更具体信息。

- **3.1.3.** 单相接地短路
  - **表现：**其中一相电流显著增加，同时该相的电压下降。零序电流也会增加[4]。在有效接地的系统中，接地故障通常具有较大的零序电流[8]。
  - **SQL** 查询示例：

```
SQL
SELECT time, device_id,
       CASE
           WHEN (current_phase_a > threshold_high_current AND voltage_phase_a < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase A'
           WHEN (current_phase_b > threshold_high_current AND voltage_phase_b < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase B'
           WHEN (current_phase_c > threshold_high_current AND voltage_phase_c < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase C'
           ELSE NULL
       END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND ((current_phase_a > threshold_high_current AND voltage_phase_a < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current)
       OR (current_phase_b > threshold_high_current AND voltage_phase_b < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current)
       OR (current_phase_c > threshold_high_current AND voltage_phase_c <
```

```
threshold_low_voltage AND zero_sequence_current >
threshold_high_zero_current));
```

说明：零序电流的存在和大小是接地故障的关键指标。零序电流的阈值将取决于系统的接地配置。

- **3.1.4.** 电弧短路
  - **表现：**以不规则和波动的电流波形为特征，通常伴有高频噪声。电压也可能波动。与金属性短路相比，电弧短路的故障电流有时可能较低，这使得仅使用简单的过电流保护更难检测 [2]。
  - **SQL 查询设计考虑：**仅基于简单的阈值检测电弧短路可能具有挑战性。可能需要更先进的信号处理技术或机器学习模型。然而，作为起点，我们可以寻找电流的快速和频繁变化。
  - **SQL 查询示例（说明性 - 可能需要进一步完善）：**

```sql
SELECT time, device_id,
    CASE
        WHEN ABS(current_phase_a - LAG(current_phase_a, 1,
current_phase_a) OVER (ORDER BY time)) > threshold_rapid_change
            AND ABS(current_phase_a - LAG(current_phase_a, 2,
current_phase_a) OVER (ORDER BY time)) < threshold_rapid_change
        THEN 'Possible Arcing Fault - Phase A'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '1 minute'
 AND (ABS(current_phase_a - LAG(current_phase_a, 1, current_phase_a)
OVER (ORDER BY time)) > threshold_rapid_change
    OR ABS(current_phase_b - LAG(current_phase_b, 1, current_phase_b)
OVER (ORDER BY time)) > threshold_rapid_change
    OR ABS(current_phase_c - LAG(current_phase_c, 1, current_phase_c)
OVER (ORDER BY time)) > threshold_rapid_change);
```

说明：此查询查找最近 1 分钟内任何相中电流的突然变化，然后电流恢复到更稳定的值。threshold_rapid_change 需要进行调整，以识别不规则行为，而不会因正常的负载波动而触发。频域分析可能更有效地检测与电弧故障相关的高频分量 [11]。这可能涉及使用 TimescaleDB 扩展或与其他分析工具集成。

- **3.1.5.** 金属性短路
  - **表现：**直接的低阻抗短路，导致非常高的故障电流和显著的电压下降。保护装置应几乎立即动作 [2]。
  - **SQL 查询示例：**类似于三相或相间短路查询，但电流阈值可能更高，电压阈值更低，并且侧重于变化速度。

```SQL
SELECT time, device_id,
    CASE
        WHEN current_phase_a > threshold_very_high_current
            AND voltage_phase_a < threshold_very_low_voltage
        THEN 'Bolted Fault - Phase A'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '10 seconds'
  AND (current_phase_a > threshold_very_high_current
    OR current_phase_b > threshold_very_high_current
    OR current_phase_c > threshold_very_high_current)
  AND (voltage_phase_a < threshold_very_low_voltage
    OR voltage_phase_b < threshold_very_low_voltage
    OR voltage_phase_c < threshold_very_low_voltage);
```

说明：此查询在很短的时间窗口（10 秒）内查找极高的电流和极低的电压条件，表明存在严重且立即的故障。如果在遥测数据中记录了保护装置的极快速动作，这将是金属性短路的有力佐证。

- **3.2. 接地故障 (Ground Faults)**
  - **3.2.1. 直接接地故障**
    - **表现：**一相或多相与大地之间的低阻抗连接。这将导致零序电流显著增加。故障相的电压将下降 [7]。
    - **SQL 查询示例：**

```SQL
SELECT time, device_id,
    CASE
        WHEN zero_sequence_current > threshold_high_zero_current
            AND (voltage_phase_a < threshold_low_voltage OR voltage_phase_b < threshold_low_voltage OR voltage_phase_c < threshold_low_voltage)
        THEN 'Solid Ground Fault'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND zero_sequence_current > threshold_high_zero_current
  AND (voltage_phase_a < threshold_low_voltage OR voltage_phase_b < threshold_low_voltage OR voltage_phase_c < threshold_low_voltage);
```

说明：零序电流的大小可以指示接地故障的严重程度和类型。

- **3.2.2.** 高阻抗接地故障
  - **表现：**故障路径中具有显著阻抗的接地故障（例如，通过植被或不良连接接地的导线）。与直接接地故障相比，这会导致较低幅度的零序电流，从而更难以检测 [1]。故障相的电压可能会降低，但不一定很低。
  - **SQL 查询设计考虑：**检测高阻抗接地故障通常需要比简单的过电流或零序过电流保护更灵敏和复杂的方法。分析谐波含量或使用高级算法可能是必要的。
  - **SQL 查询示例（说明性 - 可能需要进一步完善）：**

```
SQL
SELECT time, device_id,
    CASE
        WHEN zero_sequence_current > threshold_moderate_zero_current
            AND zero_sequence_current < threshold_high_zero_current
            AND (voltage_phase_a < threshold_normal_voltage OR
voltage_phase_b < threshold_normal_voltage OR voltage_phase_c <
threshold_normal_voltage)
        THEN 'Possible High Impedance Ground Fault'
        ELSE NULL
    END AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '10 minutes'
 AND zero_sequence_current > threshold_moderate_zero_current
 AND zero_sequence_current < threshold_high_zero_current
 AND (voltage_phase_a < threshold_normal_voltage OR voltage_phase_b <
threshold_normal_voltage OR voltage_phase_c <
threshold_normal_voltage);
```

    说明：此查询查找高于中等阈值但低于高阈值的零序电流，以及相电压的轻微降低，这可能表明存在高阻抗接地故障。
    threshold_moderate_zero_current 的阈值需要仔细校准，以避免误报和漏报。

- **3.2.3.** 间歇性接地故障
  - **表现：**重复发生和清除的接地故障。这会导致灯光闪烁、设备间歇性运行以及长时间内的潜在损坏。遥测数据将显示波动的零序电流和可能的相电压 [1][2]。
  - **SQL 查询设计考虑：**需要分析一段时间内的趋势和模式。TimescaleDB 的 time_bucket 函数可用于计算特定时间窗口内零序电流尖峰的数量。
  - **SQL 查询示例：**

```
SQL
```

```
SELECT time_bucket('1 minute', time) AS minute, device_id,
    COUNT(*) AS ground_fault_count
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND zero_sequence_current > threshold_high_zero_current
GROUP BY minute, device_id
HAVING COUNT(*) > threshold_intermittent_count;
```

说明：此查询计算最近 5 分钟内每分钟零序电流超过高阈值的次数。如果计数超过某个 threshold_intermittent_count，则可能表明存在间歇性接地故障。间歇性接地故障事件的频率和持续时间可以提供有关故障性质的更多信息。

- **3.2.4.** 带电弧的接地故障
  - **表现：**类似于直接或高阻抗接地故障，但增加了电弧故障的特性（不规则电流、潜在的高频噪声）[7]。
  - **SQL 查询设计考虑：**可能涉及零序电流检测和用于电弧短路的不规则电流模式检测的组合。
  - **SQL 查询示例（说明性）：**

```
SQL
SELECT t1.time, t1.device_id, 'Ground Fault with Arc' AS fault_type
FROM telemetry_data t1
JOIN (
   SELECT time, device_id
   FROM telemetry_data
   WHERE time > NOW() - INTERVAL '1 minute'
     AND (ABS(current_phase_a - LAG(current_phase_a, 1, current_phase_a)
OVER (ORDER BY time)) > threshold_rapid_change
         OR ABS(current_phase_b - LAG(current_phase_b, 1, current_phase_b)
OVER (ORDER BY time)) > threshold_rapid_change
         OR ABS(current_phase_c - LAG(current_phase_c, 1, current_phase_c)
OVER (ORDER BY time)) > threshold_rapid_change)
) arcing_events ON t1.time = arcing_events.time AND t1.device_id =
arcing_events.device_id
WHERE t1.time > NOW() - INTERVAL '5 minutes'
  AND t1.zero_sequence_current > threshold_moderate_zero_current;
```

说明：此查询将遥测数据与一个子查询连接起来，该子查询根据快速电流变化识别潜在的电弧事件，然后筛选出零序电流也高于中等阈值的情况。零序电流增加的时间与不规则电流波动发生的时间相关联是识别此类故障的关键。

- **3.2.5.** 多点接地故障

        - **表现：**当两相或多相同时发生接地故障时发生。零序电流将升高，并且相电压将根据每个故障的位置和阻抗而受到影响。可能导致复杂的电流流向模式。
        - **SQL 查询设计考虑：**检测多点接地故障可能需要分析零序电流与各个相电流和电压的组合。
        - **SQL 查询示例（说明性）：**

```
SQL
SELECT time, device_id, 'Multiple Ground Faults' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND zero_sequence_current > threshold_very_high_zero_current
  AND (
      (current_phase_a > threshold_moderate_current AND voltage_phase_a < threshold_normal_voltage) AND
      (current_phase_b > threshold_moderate_current AND voltage_phase_b < threshold_normal_voltage)
  ); -- 示例：两相（A 和 B）出现接地故障症状
```

        说明：这是一个简化的示例，查找非常高的零序电流以及至少两相同时出现接地故障症状（中等电流增加和电压下降）的情况。具体条件取决于系统配置和多点接地故障的特性。在多点接地故障的情况下，各个相电流的总和可能不会以直接的方式等于零序电流，这需要仔细分析这些参数之间的关系。
- **3.3. 失压故障 (Loss of Voltage Faults)**
    - **3.3.1. 完全失压**
        - **表现：**所有三相电压降至接近零。除非连接的负载中存储有能量，否则所有相的电流也可能降至零 [16]。
        - **SQL 查询示例：**

```
SQL
SELECT time, device_id, 'Complete Loss of Voltage' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND voltage_phase_a < threshold_very_low_voltage
  AND voltage_phase_b < threshold_very_low_voltage
  AND voltage_phase_c < threshold_very_low_voltage;
```

        说明：所有三相电压突然同时降至接近零是主要电源中断的明显迹象。
    - **3.3.2. 相间失压**
        - **表现：**两相之间的电压显著下降，而这些相的对地电压可能仍然存在，但可能降低或不平衡。受影响相的电流也可能异常。
        - **SQL 查询示例：**

```
SQL
SELECT time, device_id, 'Phase-to-Phase Loss of Voltage' AS fault_type
```

```
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND ((voltage_phase_ab < threshold_very_low_voltage) OR
(voltage_phase_bc < threshold_very_low_voltage) OR (voltage_phase_ca <
threshold_very_low_voltage));
```

说明：监测线间电压对于检测此类故障至关重要，仅查看相地电压可能无法发现此类故障。

- **3.3.3. 瞬时电压跌落 (Sag)**
  - **表现：**一相或多相电压在短时间内下降，通常由大型电机的启动或上游故障引起。电压通常会快速恢复 [12]。
  - **SQL 查询设计考虑：**需要分析电压骤降的持续时间。TimescaleDB 的 time_bucket 和窗口函数可用于检测低于阈值特定持续时间的下降。
  - **SQL 查询示例（说明性）：**

```
SQL
SELECT time, device_id, 'Temporary Voltage Dip' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '10 minutes'
  AND voltage_phase_a < threshold_low_voltage
  AND voltage_phase_a > threshold_very_low_voltage
  AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 second') -- 检查低电
压是否持续超过 1 秒（示例）
  AND time <= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '5 seconds'); -- 并在 5
秒内恢复（示例）
```

说明：此查询查找低于低阈值但高于极低阈值且持续短时间（在此示例中为 1 到 5 秒之间）的电压降。确切的持续时间阈值需要确定。区分可能正常的瞬时电压跌落和持续欠压情况非常重要。

- **3.3.4. 持续欠压**
  - **表现：**电压长时间低于额定运行范围。这可能是由于变压器过载或长距离输电线路负载过重造成的 [4]。
  - **SQL 查询设计考虑：**类似于瞬时电压跌落，但侧重于欠压状态的较长持续时间。
  - **SQL 查询示例：**

```
SQL
SELECT time, device_id, 'Sustained Undervoltage' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '30 minutes'
  AND voltage_phase_a < threshold_low_voltage
  AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 minute'); -- 检查低电
压是否持续超过 1 分钟（示例）
```

说明：此查询检查最近 30 分钟内 A 相电压是否低于低电压阈值超过 1 分

钟。持续欠压会损坏敏感设备，并表明需要进行负载平衡或基础设施升级。

- **3.3.5.** 电压不平衡
  - **表现：**三相电压的幅值显著不同，或者相角不是 120 度 [18]。这可能是由不平衡的负载或故障引起的。
  - **SQL 查询设计考虑：**需要计算电压不平衡系数，这涉及电压的正序、负序和零序分量。这可能需要在 SQL 查询中进行更复杂的计算，或者在遥测数据中预先计算值。
  - **SQL 查询示例（说明性 - 简化）：**

```
SQL
SELECT time, device_id, 'Voltage Unbalance' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND (ABS(voltage_phase_a - voltage_phase_b) >
threshold_voltage_difference
      OR ABS(voltage_phase_b - voltage_phase_c) >
threshold_voltage_difference
      OR ABS(voltage_phase_c - voltage_phase_a) >
threshold_voltage_difference);
```

说明：此简化查询检查任意两相电压之间的绝对差值是否超过某个 threshold_voltage_difference。更准确的计算将涉及对称分量。电压不平衡会导致电机和其他三相设备的损耗增加。

- **3.4.** 过载故障 **(Overload Faults)**
  - **3.4.1.** 轻微过载
    - **表现：**一相或多相电流在短时间内略微超过额定值 [7]。可能不会立即导致保护装置跳闸，但长期来看会导致设备过热。
    - **SQL 查询示例：**

```
SQL
SELECT time, device_id, 'Minor Overload' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '15 minutes'
  AND (current_phase_a > threshold_normal_current * 1.1 -- 10% 过载（示例）
      OR current_phase_b > threshold_normal_current * 1.1
      OR current_phase_c > threshold_normal_current * 1.1)
  AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '5 minutes'); -- 持续至
少 5 分钟（示例）
```

说明：此查询检查最近 15 分钟内任何相的电流是否超过正常电流的 110% 至少 5 分钟。跟踪轻微过载有助于识别负载增加的趋势以及容量升级的需求。

  - **3.4.2.** 严重过载

- **表现：**电流显著超过额定值，可能导致快速过热和保护装置跳闸 [17]。
- **SQL 查询示例：**

```SQL
SELECT time, device_id, 'Severe Overload' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND (current_phase_a > threshold_normal_current * 1.5 -- 50% 过载（示例）
       OR current_phase_b > threshold_normal_current * 1.5
       OR current_phase_c > threshold_normal_current * 1.5)
  AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 minute'); -- 持续至少 1 分钟（示例）
```

说明：严重过载对设备和系统稳定性构成直接风险。

- **3.4.3. 短期过载**
  - **表现：**电流的暂时增加，通常是由于电机启动或设备通电时的涌流引起的。保护装置通常设计为能够承受这些短期过载。
  - **SQL 查询设计考虑：**需要区分正常的短期过载和故障情况。可能涉及查看电流尖峰的持续时间和幅度。
  - **SQL 查询示例（说明性）：**

```SQL
SELECT time, device_id, 'Short-Term Overload' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '1 minute'
  AND (current_phase_a > threshold_normal_current * 2.0 -- 100% 过载（示例）
       OR current_phase_b > threshold_normal_current * 2.0
       OR current_phase_c > threshold_normal_current * 2.0)
  AND time <= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '10 seconds'); -- 持续时间少于 10 秒（示例）
```

说明：分析短期过载的频率和持续时间有助于识别设备或启动程序中的潜在问题。

- **3.4.4. 长期过载**
  - **表现：**电流在额定值以上持续较长时间（数小时或数天）。这肯定会导致过热并缩短设备寿命 [7]。
  - **SQL 查询示例：**

```SQL
SELECT time_bucket('1 hour', time) AS hour, device_id, 'Long-Term Overload' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '1 day'
  AND (current_phase_a > threshold_normal_current * 1.05 -- 5% 过载（示例）
       OR current_phase_b > threshold_normal_current * 1.05
```

```
    OR current_phase_c > threshold_normal_current * 1.05)
GROUP BY hour, device_id
HAVING AVG(current_phase_a) > threshold_normal_current * 1.05
   OR AVG(current_phase_b) > threshold_normal_current * 1.05
   OR AVG(current_phase_c) > threshold_normal_current * 1.05;
```

说明：此查询检查过去一天内最近一小时的平均电流是否略高于正常电流，表明存在长期过载趋势。识别长期过载对于预防性维护和容量规划至关重要。

- **3.4.5.** 电机启动过载
  - **表现：**一种特定的短期过载类型，其特征是在电机启动时出现高涌流。电流通常会在几秒钟内降至正常运行水平。
  - **SQL 查询设计考虑：**可能需要识别特定设备（电机）并查找启动期间的特征电流曲线。
  - **SQL 查询示例（说明性 - 假设存在 'device_type' 字段）：**

```
SQL
SELECT time, device_id, 'Overload due to Motor Starting' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '1 minute'
  AND device_type = 'Motor'
  AND (current_phase_a > threshold_normal_current * 3.0 -- 高涌流（示例）
      OR current_phase_b > threshold_normal_current * 3.0
      OR current_phase_c > threshold_normal_current * 3.0)
  AND time <= (LAG(time, 1) OVER (PARTITION BY device_id ORDER BY time) +
INTERVAL '5 seconds'); -- 持续时间少于 5 秒（示例）
```

说明：监测电机启动电流有助于诊断电机或其启动机构的问题。

- **3.5.** 断路故障 **(Open Circuit Faults)**
  - **3.5.1.** 单相断路
    - **表现：**其中一相电流降至零，而电源侧可能仍然存在电压。连接到断相的负载将失去电源。其他两相可能出现不平衡的电流或电压 [4]。
    - **SQL 查询示例：**

```
SQL
SELECT time, device_id, 'Single-Phase Open Circuit - Phase A' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND current_phase_a < threshold_low_current
  AND voltage_phase_a > threshold_normal_voltage * 0.8; -- 电压可能仍然存在
（示例）
```

说明：单相断路会对单相负载造成严重问题，并导致系统不平衡。

  - **3.5.2.** 两相断路

- **表现：**其中两相电流降至零。这两相之间的电压也将为零。剩余相可能携带异常电流，具体取决于负载配置。
- **SQL 查询示例：**

```SQL
SELECT time, device_id, 'Two-Phase Open Circuit' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND current_phase_a < threshold_low_current
  AND current_phase_b < threshold_low_current
  AND voltage_phase_ab < threshold_low_voltage;
```

3.5.3. 三相断路

- **表现：**所有三相电流降至零。断路电源侧可能仍然存在电压。断路下游的所有负载都将失去电源。
- **SQL 查询示例：**

```SQL
SELECT time, device_id, 'Three-Phase Open Circuit' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND current_phase_a < threshold_low_current
  AND current_phase_b < threshold_low_current
  AND current_phase_c < threshold_low_current;
```

3.5.4. 间歇性断路

- **表现：**电路重复断开和闭合，导致电流和电压波动。可能是由于连接松动或开关设备故障引起的 [12]。
- **SQL 查询设计考虑：**类似于间歇性接地故障，需要分析短时间内电流降至接近零的趋势。
- **SQL 查询示例（说明性）：**

```SQL
SELECT time_bucket('1 minute', time) AS minute, device_id,
       COUNT(*) AS open_circuit_count
FROM telemetry_data
WHERE time > NOW() - INTERVAL '5 minutes'
  AND current_phase_a < threshold_low_current
GROUP BY minute, device_id
HAVING COUNT(*) > threshold_intermittent_count;
```

说明：此查询计算最近 5 分钟内每分钟 A 相电流降至低阈值以下的次数。计数较高可能表明存在间歇性断路。

- **3.5.5.** 中性线断路
  - **表现：**三相四线系统中的中性线断开。这会导致连接到不同相的单相负载出现不平衡的电压，一些负载电压过高，而另一些负载电压过低。相电流也可能不平衡。
  - **SQL 查询设计考虑：**需要分析相零电压（如果可用）并查找显著的不平衡。此外，分析相电流和零序电流之间的关系可能提供线索。
  - **SQL 查询示例（说明性 - 假设存在 'voltage_neutral_a'、'voltage_neutral_b'、'voltage_neutral_c' 字段）：**

```
SQL
SELECT time, device_id, 'Open Neutral' AS fault_type
FROM telemetry_data
WHERE time > NOW() - INTERVAL '10 minutes'
  AND (ABS(voltage_neutral_a - threshold_normal_voltage) >
threshold_voltage_deviation
       OR ABS(voltage_neutral_b - threshold_normal_voltage) >
threshold_voltage_deviation
       OR ABS(voltage_neutral_c - threshold_normal_voltage) >
threshold_voltage_deviation);
```

说明：此查询检查任何相与中性线之间的电压是否与正常电压存在显著偏差。中性线断路是一种严重的情况，可能会损坏电器。

有效的故障检测 SQL 查询的设计需要仔细考虑每种故障类型的具体电气特性、可用的遥测数据字段以及适当的阈值。利用 TimescaleDB 的时序函数可以分析时间模式和趋势，从而提高故障检测的准确性和鲁棒性。查询的复杂性范围从简单的阈值检查到涉及变化率、持续时间和多个参数组合的更复杂的分析。

以下表格总结了上述分析中确定的故障类型、典型的电气表现以及需要监测的关键遥测参数：

表 1：故障类型、电气表现与关键遥测参数映射

主要故障类型	二级分类	典型电气表现	关键遥测参数
短路故障	三相短路	所有三相电流急剧增加，所有三相电压显著下降	current_phase_a/b/c, voltage_phase_a/b/c
短路故障	相间短路	两相电流显著增加，这两相之间电压下降	current_phase_a/b/c, voltage_phase_ab/bc/ca

短路故障	单相接地短路	一相电流显著增加，该相电压下降，零序电流增加	current_phase_a/b/c, voltage_phase_a/b/c, zero_sequence_current
短路故障	电弧短路	电流波形不规则波动，可能存在高频噪声，电压可能波动	current_phase_a/b/c, voltage_phase_a/b/c
短路故障	金属性短路	非常高的故障电流，显著的电压下降	current_phase_a/b/c, voltage_phase_a/b/c
接地故障	直接接地故障	零序电流显著增加，故障相电压下降	zero_sequence_current, voltage_phase_a/b/c
接地故障	高阻抗接地故障	零序电流中等程度增加，故障相电压可能略有下降	zero_sequence_current, voltage_phase_a/b/c
接地故障	间歇性接地故障	零序电流波动，可能伴随相电压波动	zero_sequence_current, voltage_phase_a/b/c
接地故障	带电弧的接地故障	零序电流增加，电流波形不规则波动	zero_sequence_current, current_phase_a/b/c
接地故障	多点接地故障	零序电流非常高，至少两相出现接地故障症状	zero_sequence_current, current_phase_a/b/c, voltage_phase_a/b/c
失压故障	完全失压	所有三相电压降至接近零	voltage_phase_a/b/c
失压故障	相间失压	两相之间电压显著下降	voltage_phase_ab/bc/ca
失压故障	瞬时电压跌落	一相或多相电压在短时间内下降	voltage_phase_a/b/c

失压故障	持续欠压	一相或多相电压长时间低于正常水平	voltage_phase_a/b/c
失压故障	电压不平衡	三相电压幅值差异显著	voltage_phase_a/b/c
过载故障	轻微过载	一相或多相电流略微超过额定值，持续一段时间	current_phase_a/b/c
过载故障	严重过载	电流显著超过额定值	current_phase_a/b/c
过载故障	短期过载	电流的暂时增加，持续时间较短	current_phase_a/b/c
过载故障	长期过载	电流长时间高于额定值	current_phase_a/b/c
过载故障	电机启动过载	电机启动时出现高涌流，持续时间较短	current_phase_a/b/c, device_type
断路故障	单相断路	一相电流降至零，电压可能仍然存在	current_phase_a/b/c, voltage_phase_a/b/c
断路故障	两相断路	两相电流降至零，这两相之间电压为零	current_phase_a/b/c, voltage_phase_ab/bc/ca
断路故障	三相断路	所有三相电流降至零	current_phase_a/b/c
断路故障	间歇性断路	电流和电压波动	current_phase_a/b/c, voltage_phase_a/b/c
断路故障	中性线断路	相零电压不平衡	voltage_neutral_a/b/c

以下表格列出了在上述分析中为每个二级故障分类开发的示例 SQL 查询：

表 2：故障检测示例 **SQL** 查询

故障类型	**SQL** 查询
三相短路	SELECT time, device_id, CASE WHEN

	current_phase_a > threshold_high_current AND current_phase_b > threshold_high_current AND current_phase_c > threshold_high_current AND voltage_phase_a < threshold_low_voltage AND voltage_phase_b < threshold_low_voltage AND voltage_phase_c < threshold_low_voltage THEN 'Three-Phase Short Circuit' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND (current_phase_a > threshold_high_current OR current_phase_b > threshold_high_current OR current_phase_c > threshold_high_current) AND (voltage_phase_a < threshold_low_voltage OR voltage_phase_b < threshold_low_voltage OR voltage_phase_c < threshold_low_voltage);
相间短路	SELECT time, device_id, CASE WHEN (current_phase_a > threshold_high_current AND current_phase_b > threshold_high_current AND voltage_phase_ab < threshold_low_voltage) OR (current_phase_b > threshold_high_current AND current_phase_c > threshold_high_current AND voltage_phase_bc < threshold_low_voltage) OR (current_phase_c > threshold_high_current AND current_phase_a > threshold_high_current AND voltage_phase_ca < threshold_low_voltage) THEN 'Phase-to-Phase Short Circuit' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND ((current_phase_a > threshold_high_current AND current_phase_b > threshold_high_current AND voltage_phase_ab < threshold_low_voltage) OR (current_phase_b > threshold_high_current AND current_phase_c > threshold_high_current AND voltage_phase_bc < threshold_low_voltage) OR (current_phase_c > threshold_high_current AND current_phase_a > threshold_high_current AND voltage_phase_ca < threshold_low_voltage));
单相接地短路 - A 相	SELECT time, device_id, CASE WHEN (current_phase_a > threshold_high_current AND voltage_phase_a < threshold_low_voltage AND zero_sequence_current >

	threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase A' WHEN (current_phase_b > threshold_high_current AND voltage_phase_b < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase B' WHEN (current_phase_c > threshold_high_current AND voltage_phase_c < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) THEN 'Single-Phase-to-Ground Short Circuit - Phase C' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND ((current_phase_a > threshold_high_current AND voltage_phase_a < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) OR (current_phase_b > threshold_high_current AND voltage_phase_b < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current) OR (current_phase_c > threshold_high_current AND voltage_phase_c < threshold_low_voltage AND zero_sequence_current > threshold_high_zero_current));
可能的电弧短路 - A 相	SELECT time, device_id, CASE WHEN ABS(current_phase_a - LAG(current_phase_a, 1, current_phase_a) OVER (ORDER BY time)) > threshold_rapid_change AND ABS(current_phase_a - LAG(current_phase_a, 2, current_phase_a) OVER (ORDER BY time)) < threshold_rapid_change THEN 'Possible Arcing Fault - Phase A' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '1 minute' AND (ABS(current_phase_a - LAG(current_phase_a, 1, current_phase_a) OVER (ORDER BY time)) > threshold_rapid_change OR ABS(current_phase_b - LAG(current_phase_b, 1, current_phase_b) OVER (ORDER BY time)) > threshold_rapid_change OR

	ABS(current_phase_c - LAG(current_phase_c, 1, current_phase_c) OVER (ORDER BY time)) > threshold_rapid_change);
金属性短路 - A 相	SELECT time, device_id, CASE WHEN current_phase_a > threshold_very_high_current AND voltage_phase_a < threshold_very_low_voltage THEN 'Bolted Fault - Phase A' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '10 seconds' AND (current_phase_a > threshold_very_high_current OR current_phase_b > threshold_very_high_current OR current_phase_c > threshold_very_high_current) AND (voltage_phase_a < threshold_very_low_voltage OR voltage_phase_b < threshold_very_low_voltage OR voltage_phase_c < threshold_very_low_voltage);
直接接地故障	SELECT time, device_id, CASE WHEN zero_sequence_current > threshold_high_zero_current AND (voltage_phase_a < threshold_low_voltage OR voltage_phase_b < threshold_low_voltage OR voltage_phase_c < threshold_low_voltage) THEN 'Solid Ground Fault' ELSE NULL END AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND zero_sequence_current > threshold_high_zero_current AND (voltage_phase_a < threshold_low_voltage OR voltage_phase_b < threshold_low_voltage OR voltage_phase_c < threshold_low_voltage);
可能的高阻抗接地故障	SELECT time, device_id, CASE WHEN zero_sequence_current > threshold_moderate_zero_current AND zero_sequence_current < threshold_high_zero_current AND (voltage_phase_a < threshold_normal_voltage OR voltage_phase_b < threshold_normal_voltage OR voltage_phase_c < threshold_normal_voltage) THEN 'Possible High Impedance Ground Fault' ELSE NULL END

	AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '10 minutes' AND zero_sequence_current > threshold_moderate_zero_current AND zero_sequence_current < threshold_high_zero_current AND (voltage_phase_a < threshold_normal_voltage OR voltage_phase_b < threshold_normal_voltage OR voltage_phase_c < threshold_normal_voltage);
间歇性接地故障	SELECT time_bucket('1 minute', time) AS minute, device_id, COUNT(*) AS ground_fault_count FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND zero_sequence_current > threshold_high_zero_current GROUP BY minute, device_id HAVING COUNT(*) > threshold_intermittent_count;
带电弧的接地故障	SELECT t1.time, t1.device_id, 'Ground Fault with Arc' AS fault_type FROM telemetry_data t1 JOIN (SELECT time, device_id FROM telemetry_data WHERE time > NOW() - INTERVAL '1 minute' AND (ABS(current_phase_a - LAG(current_phase_a, 1, current_phase_a) OVER (ORDER BY time)) > threshold_rapid_change OR ABS(current_phase_b - LAG(current_phase_b, 1, current_phase_b) OVER (ORDER BY time)) > threshold_rapid_change OR ABS(current_phase_c - LAG(current_phase_c, 1, current_phase_c) OVER (ORDER BY time)) > threshold_rapid_change)) arcing_events ON t1.time = arcing_events.time AND t1.device_id = arcing_events.device_id WHERE t1.time > NOW() - INTERVAL '5 minutes' AND t1.zero_sequence_current > threshold_moderate_zero_current;
多点接地故障	SELECT time, device_id, 'Multiple Ground Faults' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND zero_sequence_current > threshold_very_high_zero_current AND (

	(current_phase_a > threshold_moderate_current AND voltage_phase_a < threshold_normal_voltage) AND (current_phase_b > threshold_moderate_current AND voltage_phase_b < threshold_normal_voltage));
完全失压	SELECT time, device_id, 'Complete Loss of Voltage' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND voltage_phase_a < threshold_very_low_voltage AND voltage_phase_b < threshold_very_low_voltage AND voltage_phase_c < threshold_very_low_voltage;
相间失压	SELECT time, device_id, 'Phase-to-Phase Loss of Voltage' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND ((voltage_phase_ab < threshold_very_low_voltage) OR (voltage_phase_bc < threshold_very_low_voltage) OR (voltage_phase_ca < threshold_very_low_voltage));
瞬时电压跌落	SELECT time, device_id, 'Temporary Voltage Dip' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '10 minutes' AND voltage_phase_a < threshold_low_voltage AND voltage_phase_a > threshold_very_low_voltage AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 second') AND time <= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '5 seconds');
持续欠压	SELECT time, device_id, 'Sustained Undervoltage' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '30 minutes' AND voltage_phase_a < threshold_low_voltage AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 minute');

电压不平衡	SELECT time, device_id, 'Voltage Unbalance' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND (ABS(voltage_phase_a - voltage_phase_b) > threshold_voltage_difference OR ABS(voltage_phase_b - voltage_phase_c) > threshold_voltage_difference OR ABS(voltage_phase_c - voltage_phase_a) > threshold_voltage_difference);
轻微过载	SELECT time, device_id, 'Minor Overload' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '15 minutes' AND (current_phase_a > threshold_normal_current * 1.1 OR current_phase_b > threshold_normal_current * 1.1 OR current_phase_c > threshold_normal_current * 1.1) AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '5 minutes');
严重过载	SELECT time, device_id, 'Severe Overload' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND (current_phase_a > threshold_normal_current * 1.5 OR current_phase_b > threshold_normal_current * 1.5 OR current_phase_c > threshold_normal_current * 1.5) AND time >= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '1 minute');
短期过载	SELECT time, device_id, 'Short-Term Overload' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '1 minute' AND (current_phase_a > threshold_normal_current * 2.0 OR current_phase_b > threshold_normal_current * 2.0 OR current_phase_c > threshold_normal_current * 2.0) AND time <= (LAG(time, 1) OVER (ORDER BY time) + INTERVAL '10 seconds');
长期过载	SELECT time_bucket('1 hour', time) AS hour, device_id, 'Long-Term Overload' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '1 day' AND (current_phase_a > threshold_normal_current * 1.05 OR

	current_phase_b > threshold_normal_current * 1.05 OR current_phase_c > threshold_normal_current * 1.05) GROUP BY hour, device_id HAVING AVG(current_phase_a) > threshold_normal_current * 1.05 OR AVG(current_phase_b) > threshold_normal_current * 1.05 OR AVG(current_phase_c) > threshold_normal_current * 1.05;
电机启动过载	SELECT time, device_id, 'Overload due to Motor Starting' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '1 minute' AND device_type = 'Motor' AND (current_phase_a > threshold_normal_current * 3.0 OR current_phase_b > threshold_normal_current * 3.0 OR current_phase_c > threshold_normal_current * 3.0) AND time <= (LAG(time, 1) OVER (PARTITION BY device_id ORDER BY time) + INTERVAL '5 seconds');
单相断路 - A 相	SELECT time, device_id, 'Single-Phase Open Circuit - Phase A' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND current_phase_a < threshold_low_current AND voltage_phase_a > threshold_normal_voltage * 0.8;
两相断路	SELECT time, device_id, 'Two-Phase Open Circuit' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND current_phase_a < threshold_low_current AND current_phase_b < threshold_low_current AND voltage_phase_ab < threshold_low_voltage;
三相断路	SELECT time, device_id, 'Three-Phase Open Circuit' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND current_phase_a < threshold_low_current AND current_phase_b < threshold_low_current AND current_phase_c < threshold_low_current;

间歇性断路	SELECT time_bucket('1 minute', time) AS minute, device_id, COUNT(*) AS open_circuit_count FROM telemetry_data WHERE time > NOW() - INTERVAL '5 minutes' AND current_phase_a < threshold_low_current GROUP BY minute, device_id HAVING COUNT(*) > threshold_intermittent_count;
中性线断路	SELECT time, device_id, 'Open Neutral' AS fault_type FROM telemetry_data WHERE time > NOW() - INTERVAL '10 minutes' AND (ABS(voltage_neutral_a - threshold_normal_voltage) > threshold_voltage_deviation OR ABS(voltage_neutral_b - threshold_normal_voltage) > threshold_voltage_deviation OR ABS(voltage_neutral_c - threshold_normal_voltage) > threshold_voltage_deviation);

4. 实时故障检测与阈值设定

所设计的 SQL 查询可以集成到实时监控系统中。当新的 FTU 数据被摄取到 TimescaleDB 数据仓库中时，可以连续或定期执行这些查询，以检查是否存在故障情况。如果查询返回指示故障的结果，则可以触发警报，向操作员提供潜在问题的即时通知及其分类。

为每个电气参数（例如，电流、电压、零序电流）设置适当的阈值对于准确检测故障，同时最大限度地减少误报和漏报至关重要。确定这些阈值的方法包括：

- **历史数据统计分析：**分析正常运行条件下的历史遥测数据，以建立基线值及其统计变化（例如，平均值、标准差）。阈值可以基于这些统计数据来设置（例如，与平均值相差一定数量的标准差）[20]。
- **设备规格和标准：**参考制造商的规格和相关的行业标准，以确定电流、电压等的安全运行限制 [18]。阈值应设置在这些限制范围内。
- **专家知识和经验数据：**利用电力系统工程师和操作员的经验和知识，以及来自真实故障事件的数据，来完善阈值。
- **自适应阈值：**考虑实施可以根据网络的当前运行条件和负载水平进行调整的自适应阈值 [22]。

需要根据故障检测系统的性能以及网络配置或负载模式的任何变化，定期审查和调整阈值。有效的实时故障检测需要在灵敏度（可靠地检测故障）和特异性（避免误报 ）之间取得平衡。阈值是实现这种平衡的关键，其确定是一个迭代过程，应基于数据、专业知识和对系

统性能的持续监控。将阈值设置得过低会导致由于正常的系统波动而频繁出现误报，这可能会使操作员不堪重负并降低他们对系统的信任。相反，将阈值设置得过高可能会导致错过实际故障的检测，从而可能导致更严重的后果。因此，数据驱动的方法与专家知识相结合对于建立适当的阈值至关重要。分析历史数据以了解不同参数在正常运行条件下的典型值范围可以为设置初始阈值提供统计基础。然后可以根据实际经验和操作员的反馈来微调这些阈值。此外，考虑随系统运行状态变化的自适应阈值（例如，在峰值负载期间更高的电流阈值）可以提高故障检测的准确性。

以下表格概述了设置阈值的不同策略以及每个参数需要考虑的关键因素：

表 **3**：建议的阈值策略和考虑因素

电气参数	阈值策略	关键考虑因素
电流（各相）	统计分析、设备规格、专家知识、自适应阈值	正常负载波动、设备额定电流、保护装置跳闸特性、环境温度
电压（各相）	统计分析、设备规格、专家知识	正常电压范围、设备耐压能力、电压质量标准
零序电流	统计分析、系统接地配置、专家知识	正常泄漏电流水平、接地保护灵敏度
线间电压	统计分析、设备规格、专家知识	正常运行时的平衡情况、相间绝缘强度

5. 结论

本报告总结了关键发现，包括所分析故障类型的典型电气表现以及用于在 TimescaleDB 数据仓库中进行实时检测的相应 SQL 查询设计。准确的故障检测对于配网设备的可靠性和安全性至关重要。使用 TimescaleDB 等时序数据库分析遥测数据和实施实时故障监控具有显著优势。为了确保故障检测系统的有效性，需要仔细考虑并持续完善阈值。

潜在的后续步骤包括：在实时监控平台中实施所设计的 SQL 查询；使用历史和实时遥测数据验证查询的准确性和性能；开发可视化仪表板以显示故障警报和趋势；探索更高级的异常检测技术，包括机器学习模型，以检测复杂或微妙的故障情况 [23]。

本报告为使用遥测数据和 TimescaleDB 对配网设备进行实时故障检测提供了一个基础框架。通过实施这些策略并根据运营经验不断改进系统，可以显著提高网络监控、维护和整体可靠性。

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