

# 智烽维科技 (CDA) 技术白皮书： 超级电容器漏电流与自放电特性深度解析

## CDA Technology Whitepaper: In-depth Analysis of Supercapacitor Leakage Current and Self-Discharge Characteristics

### 致尊敬的客户及合作伙伴：

To Our Esteemed Customers and Partners:

在超级电容器及锂离子电容器的实际应用中，尤其是在微功耗系统、能量收集（Energy Harvesting）以及长时间 RTC 备用电源设计中，漏电流(Leakage Current) 和自放电 (Self-Discharge) 是工程师最关注的两个核心指标。这两个参数在物理本质上同宗同源，但在工程测试与系统影响上却有着不同的表现形式。本白皮书旨在为您深度剖析这两大特性的物理机制、测试标准及其对终端设计的具体影响，协助贵司优化整体电路方案。

In practical applications of supercapacitors and lithium-ion capacitors, especially in micro-power systems, energy harvesting, and long-term RTC backup power designs, Leakage Current and Self-Discharge are the two core metrics engineers care about most. These two parameters share the same physical origin but manifest differently in engineering tests and system impacts. This whitepaper aims to deeply analyze the physical mechanisms, testing standards, and specific impacts on terminal design of these two characteristics, helping your company optimize the overall circuit solution.

## 一、 核心概念解析：漏电流与自放电

### I . Core Concept Analysis: Leakage Current and Self-Discharge

## 1. 漏电流 (Leakage Current, LC) —— “插着电时的微小损耗”

### 1. Leakage Current (LC) - "Tiny Loss When Plugged In"

理想的超级电容器内部不导电，但实际器件内部存在着微小的等效并联电阻 (Equivalent Parallel Resistance,  $R_p$ )。当超级电容器连接在外部电源上，且两端保持恒定的额定电压 ( $V_{rated}$ ) 时，为了补偿由  $R_p$  引起的内部电荷流失，外部电源必须持续提供一个极小的直流补偿电流，这就是稳态漏电流。

An ideal supercapacitor is non-conductive internally, but real devices have a tiny Equivalent Parallel Resistance ( $R_p$ ). When a supercapacitor is connected to an external power supply and maintained at a constant rated voltage ( $V_{rated}$ ), the external supply must continuously provide a minimal DC compensation current to replenish the internal charge loss caused by  $R_p$ . This is the steady-state leakage current.

- 参数示例：18 $\mu$ A@72hrs

Parameter Example: 18 $\mu$ A@72hrs

- 含义：在室温下恒压充电 72 小时后，维持电容满电状态所需的外部微小电流不超过 18 $\mu$ A。

Meaning: After charging at a constant voltage for 72 hours at room temperature, the external tiny current required to maintain the capacitor fully charged does not exceed 18 $\mu$ A.

## 2. 自放电 (Self-Discharge, SD) —— “断开电后的电压回落”

### 2. Self-Discharge (SD) - "Voltage Drop After Disconnection"

当超级电容器完全充满电，并彻底断开外部电源（开路状态）后，由于内部等效并联电阻 ( $R_p$ ) 的存在，电容器内部的正负电荷会缓慢地发生中和（即内部漏电）。这种电荷的内部流失，宏观上表现为电容器两端电压随时间的自然下降，这就是自放电。

When the supercapacitor is fully charged and completely disconnected from the external power supply (open circuit), the positive and negative charges inside slowly neutralize due to the internal Equivalent Parallel Resistance ( $R_p$ ) (i.e., internal leakage). This internal loss of charge macroscopically manifests as a natural drop in voltage across the capacitor over time, which is self-discharge.

- 参数示例：Voltage drop  $\leq 5\%$  after 72 hours

Parameter Example: Voltage drop  $\leq 5\%$  after 72 hours

- 含义：将电容充满电并静置 72 小时后，其电压下降的幅度。

Meaning: The magnitude of voltage drop after the capacitor is fully charged and left standing for 72 hours.

## 二、漏电流与自放电的内在联系与区别

### II. Internal Connection and Difference Between Leakage Current and Self-Discharge

为了便于贵司工程师理解，我们可以将这两个参数视为“一枚硬币的正反面”，它们都主要由电容器内部的杂质、电解液稳定性以及电荷重分布（Charge Redistribution）引起。

To facilitate understanding by your engineers, we can view these two parameters as "two sides of the same coin." They are both primarily caused by internal impurities, electrolyte stability, and charge redistribution.

| 对比维度 / Dimension           | 漏电流 / Leakage Current               | 自放电 / Self-Discharge              |
|----------------------------|-------------------------------------|-----------------------------------|
| 外部状态<br>External State     | 连接外部电源<br>Connected to power        | 断开外部电源<br>Disconnected from power |
| 测量对象<br>Measurement Target | 微小电流 ( $\mu A/mA$ )<br>Tiny current | 电压下降幅度 (V)<br>Voltage drop        |
| 物理本质<br>Physical Essence   | 外部电源的实时补偿<br>Real-time compensation | 储能自然流失<br>Natural energy loss     |

### 工程提示 (Engineering Tip):

很多工程师在测试自放电时，往往充电几分钟后就断开电源开始观察电压。此时电压会发生剧烈下降，但这并不是真正的自放电，而是离子向多孔碳内部微孔深处扩散的电荷重分布现象。严谨的自放电测试，必须先进行长时间的恒压充电（通常要求 8 小时以上），让内部电荷完全平衡后，再断开电源测量电压衰减。

Many engineers disconnect the power and start observing the voltage just minutes after charging when testing self-discharge. The severe voltage drop that occurs is not true self-discharge, but charge redistribution. A rigorous self-discharge test must first involve long-term constant voltage charging (usually over 8 hours) to allow internal charges to balance completely before disconnecting the power to measure voltage decay.

### 三、这两个参数对终端设计有什么具体影响？

#### III. Specific Impacts of These Two Parameters on Terminal Design?

##### 1. 并联电池系统（看重“漏电流”）：

在智能水表、气表等应用中，超级电容通常与一次性电池并联。此时，电容一直处于被外部电源（电池）充电的状态。因此，决定电池寿命的是漏电流。18 $\mu$ A 的漏电流将作为系统额外的静态功耗，持续消耗电池电量。

##### 1. Parallel Battery Systems (Focus on "Leakage Current"):

In applications like smart meters, supercapacitors are usually paralleled with primary batteries. The capacitor is constantly being charged by the external battery. Therefore, leakage current determines battery life. An 18 $\mu$ A leakage current continuously consumes battery power as static power consumption.

##### 2. 主电源断电备用系统（看重“自放电”）：

在行车记录仪、工控主板等应用中，当主电源突然断电后，超级电容需要为 RTC (实时时钟) 或 SRAM 供电。此时，电容处于放电状态。系统能维持多长时间，取决于电容自身的自放电速率。自放电越小，电压下降越慢，维持时间越长。

##### 2. Main Power Failure Backup Systems (Focus on "Self-Discharge"):

In applications like dashcams and industrial motherboards, supercapacitors supply power to RTC or SRAM when main power fails. The duration the system can be maintained depends on the capacitor's self-discharge rate. Lower self-discharge means slower voltage drop and longer retention time.

##### 3. 微能量收集系统 (Energy Harvesting):

对于太阳能或压电收集系统，漏电流和自放电同样重要。极小的漏电流能确保微弱的收集电流可以将其充满；而极低的自放电能确保收集到的能量在无外部输入的夜晚或静止状态下得以长久保存。

##### 3. Micro Energy Harvesting Systems:

For solar or piezoelectric harvesting systems, both leakage current and self-discharge are crucial. Minimal leakage current ensures weak harvested currents can fully charge it, while ultra-low self-discharge ensures stored energy is preserved during nights or idle states without external input.

为协助贵司研发工程师更直观地理解漏电流 (Leakage Current) 与自放电 (Self-Discharge) 在实际测试中的动态表现, 本附录特别提供了标准的测试演变曲线。以下图表直观揭示了超级电容器在充电与静置过程中的物理微观变化。

To assist your R&D engineers in intuitively understanding the dynamic performance of Leakage Current and Self-Discharge during actual testing, this appendix provides standard testing evolution curves. The following charts visually reveal the physical microscopic changes of supercapacitors during charging and resting.

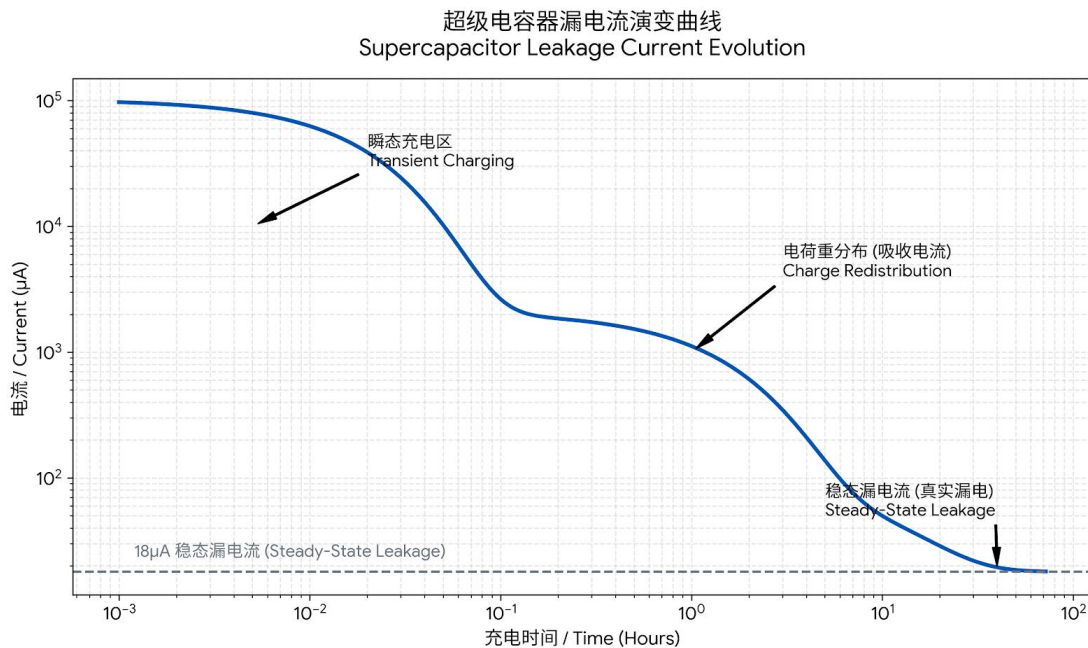
## 一、超级电容器漏电流演变曲线解析

### I. Analysis of Supercapacitor Leakage Current Evolution Curve

由于超级电容在接通电源瞬间的充电电流极大 (安培级), 而最终趋于稳定的漏电流极小 (微安级), 跨度可达数万倍, 因此本图表采用了双对数坐标轴 (Log-Log Scale) 进行绘制。

Because the charging current of a supercapacitor at the moment of power-on is extremely large (ampere level), while the final steady leakage current is extremely small (microampere level), spanning tens of thousands of times, this chart uses a Log-Log Scale for precise plotting.

#### 【图表解读 Chart Interpretation】:



- **瞬态充电区 (Transient Charging):** 在接通额定电压的最初几秒到几分钟内, 电流急剧下降。此时外部电源主要用于克服等效串联电阻 (ESR) 并建立表面宏观电荷。

Transient Charging: In the first few seconds to minutes of applying the rated voltage, the current drops sharply. The external power supply is primarily used to overcome ESR and establish surface macroscopic charge.

- **电荷重分布/吸收电流 (Charge Redistribution):** 曲线中段 (通常在几小时到几十小时之间) 展现了一个漫长的缓坡。这是由于电解液离子需要克服极化阻力, 缓慢渗透到多孔活性炭极细微的孔洞深处。此时测试仪器上显示的电流并非真实漏电, 而是内部正在“消化”电荷的吸收电流。

Charge Redistribution: The middle section of the curve (usually between hours and tens of hours) shows a long gentle slope. This is because electrolyte ions need to overcome polarization resistance and slowly penetrate deep into the microscopic pores of the porous activated carbon. The current

shown on the tester at this time is not real leakage, but an absorption current as the interior "digests" charges.

- **稳态漏电流 (Steady-State Leakage):** 如图所示, 只有在严格保持恒压充电 **72 小时** 后, 曲线才真正趋于水平。此时吸收电流耗尽, 图表中指向的极低电流值 (例如  $18\mu\text{A}$ ) 才是由纯内部杂质引起的真实漏电流。

Steady-State Leakage: As shown in the chart, only after strictly maintaining constant voltage charging for **72 hours** does the curve truly level off. At this point, the absorption current is exhausted, and the extremely low current value indicated (e.g.,  $18\mu\text{A}$ ) is the true leakage current caused purely by internal impurities.

**工程结论:** 提前 (如 12 小时) 读取漏电流数据会导致严重的高估。严格遵循 72 小时测试标准, 是获取系统真实静态功耗基准的唯一途径。

**Engineering Conclusion:** Reading leakage current data prematurely (e.g., at 12 hours) leads to severe overestimation. Strictly following the 72-hour test standard is the only way to obtain a true baseline for the system's static power consumption.

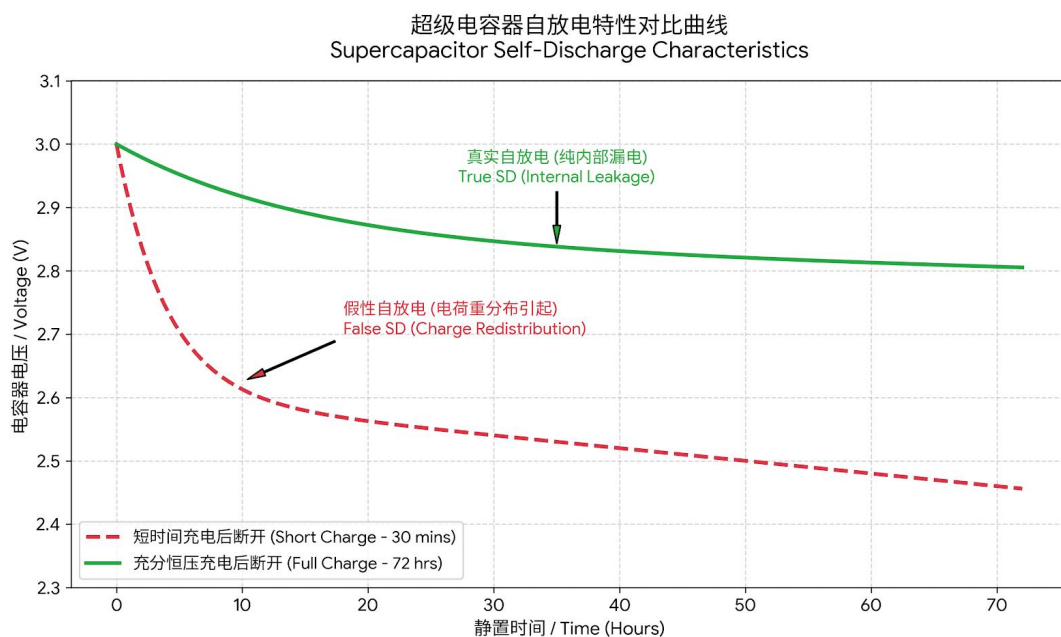
## 二、 超级电容器自放电特性对比曲线解析

### II. Analysis of Supercapacitor Self-Discharge Characteristics Curve

自放电测试 (开路电压跌落) 是评估电容“保电能力”的核心。本图表通过两条对比曲线, 清晰界定了“真实自放电”与“假性自放电”的区别。

Self-discharge testing (open-circuit voltage drop) is core to evaluating a capacitor's "charge retention capability." This chart clearly distinguishes between "true self-discharge" and "false self-discharge" through two contrasting curves.

【图表解读 Chart Interpretation】:



- **假性自放电 (红色虚线 / False SD):** 若电容器仅充电 30 分钟便断开电源, 其开路电压会发生剧烈的陡降。这并非电容漏电, 而是由于前文提到的“电荷重分布”未完成——表面电荷向内部微孔深处扩散, 导致宏观电压被迅速拉低。

False SD (Red Dashed Line): If the capacitor is charged for only 30 minutes and then disconnected, its open-circuit voltage will experience a sharp, steep drop. This is not capacitor leakage, but rather because the aforementioned "charge redistribution" is incomplete—surface charges diffuse deep into internal micro-pores, causing the macroscopic voltage to be rapidly pulled down.

- **真实自放电（绿色实线 / True SD）：** 经过 72 小时充分恒压充电、让内部电荷达到绝对平衡后再断开电源，电容呈现出真实的非线性自然衰减规律。
  - **非线性特征：** 在断开初期的前 10-20 小时内，由于残余微弱极化的释放，电压下降速率略快；随后，曲线迅速趋于平缓，展现出极低的内部自耗散。
  - **高压保持率：** 优异的电容器在 72 小时静置结束后，其电压降幅极小（如图所示保持在 2.80V 左右，远高于常规的 2.4V 额定电压的80%规格控制线）。
- True SD (Green Solid Line): After 72 hours of full constant voltage charging, allowing internal charges to reach absolute equilibrium before disconnecting, the capacitor exhibits a true non-linear natural decay pattern.
- **Non-linear Feature:** In the first 10-20 hours after disconnection, the voltage drop rate is slightly faster due to the release of residual weak polarization; subsequently, the curve quickly flattens out, demonstrating extremely low internal self-dissipation.
  - **High Voltage Retention:** An excellent capacitor will have a minimal voltage drop after 72 hours of resting (As shown in the figure, it remains at approximately 2.80V, which is much higher than the 80% specification control line of the conventional 2.4V rated voltage).

**工程结论：** 在设计诸如 RTC 时钟保持等断电备用电路时，必须参考充分充电后的真实自放电曲线。CDA 智烽维优异的电压保持能力（绿色实线特性）将显著延长贵司终端设备的数据安全驻留时间。

**Engineering Conclusion:** When designing power-off backup circuits such as RTC clock retention, the true self-discharge curve after full charging must be referenced. CDA's excellent voltage retention capability (green solid line characteristics) will significantly extend the data security retention time of your terminal equipment.