



## Explanation of Inverter DC Capacitance and Inrush Current

**1. What is Inverter DC Capacitance?** All modern power inverters have a large capacitor bank at their DC input terminals to help provide smooth power conversion from DC to an AC sine wave and back to DC when charging the battery. The amount of DC capacitance is typically proportional to the inverter's surge rating, which is typically proportional to the inverter's size and cost. We say "typically" because specific inverter models also vary in other related specs, such as inductance and operating frequency, which are all related along with capacitance to the inverter's cost, size, and surge performance. The amount of inductance and capacitance, among other things, is what separates an 80lb \$1500 inverter (Victron, Magnum) from a 20lb \$1000 inverter (Xantrex, Kisae).

**2. What is Inrush Current?** During initial DC power connection to the inverter (a.k.a. cold start), the capacitor is in a discharged state and acts as a short circuit, until it accumulates some electric charge, which causes its voltage to rise. When initially connecting a battery to an inverter's capacitive DC input, there is an inrush of current as the input capacitance is charged up to the battery voltage. Inrush is a transient event, which means it happens in a very short time, typically measured in milliseconds, and its peak current is only limited by a total resistance of the battery-inverter electrical circuit. This resistance is low, so the peak current is high, which can be damaging to sensitive electronic components if it exceeds their maximum ratings. Note that inrush only happens when the DC power circuit is switched on, not when the inverter itself is turned on to produce AC power. If the inverter is turned off from its control panel and then on again, while the DC disconnect switch remains on, there is no inrush in that situation as the DC capacitors remain charged even when the inverter is turned off at the control panel.

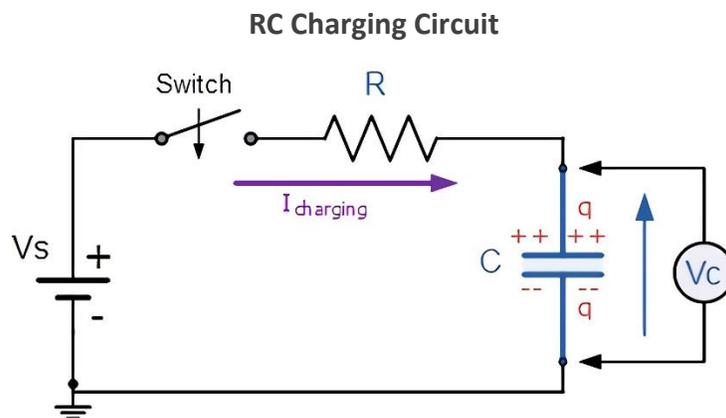
**3. How much Inrush Current do I have in my system and how do I measure it?** Due to its short transient nature the inrush is very difficult to measure and requires specially designed tools to measure it. You cannot measure inrush with a typical Digital Voltage Meter (DVM) or Ammeter. You can calculate inrush if you know the resistance of all components in the circuit and apply Ohm's law using the battery Voltage  $I = V/R$ , but measuring very low resistance is just as difficult, so you must approximate DC resistance with AC impedance of low frequency, which is a method used by specially designed tools, such as Hioki BT3554 battery tester, which costs around \$3000. Recently some cheaper alternatives appeared on the market, such as the [YR1035 Battery Internal Resistance Test Meter](#).

The rest of this paper will focus on detailed explanations and examples of inrush measurement and how to protect your system, but just to put things into perspective a total circuit resistance with a single Lithionics 315Ah battery and a 3000W inverter can be as low as 5 milli-Ohm (mOhm), or 0.005 Ohm, when using short 4/0 wire to connect the battery to the inverter. With typical battery voltage of 13.5V this can result in an inrush peak current of **2,700 Amps** (!!!) or an instant power surge of **36,450 Watts** (!!!) from the battery to the inverter capacitors. This surge only lasts under one millisecond, a much shorter time than any fuse can react, but could be enough to damage the MOSFET transistors in the Battery Management System (BMS) or even damage the capacitors and other components inside the inverter. If you increase the total resistance by only 1 mOhm, the peak current is reduced by 450A, which becomes

manageable by the BMS used in the same battery, while still providing excellent performance and efficiency of the overall system. The goal is to reduce the peak inrush to under 2,400A for the Lithionics 315Ah battery, which brings the minimal required total resistance above 5.6 mOhm.

**4. How can I protect my system from Inrush related damage?** The simplest solution is to follow the battery manufacturer's guide for power circuits wiring. You might be tempted to use a larger wire gauge and/or shorter wires, as you generally want lower resistance for best power efficiency, but as shown above the resistance can be too low, so it's important to understand the limiting factors in both directions. You also might be tempted to skip on using DC disconnect switches or extra fuses, assuming that the battery's own Power ON/OFF function can be used instead of a mechanical DC disconnect switch and the BMS can be relied on to protect from overcurrent, but there can be corner cases you haven't considered where these additional safety devices become important. In some cases where a larger battery bank or a larger inverter is needed you might need an external pre-charge system (a.k.a. inrush current limiter) or an external BMS which includes a pre-charge function. Lithionics Battery offers such systems, so you should consider the limitations of batteries with an Internal BMS and consider a battery bank with an External BMS to better manage higher power, which comes with higher inrush peaks. Any system with an inverter above 2,000W should have specific ways of limiting inrush, such as estimation of circuit resistance, and above 3,000W should consider External BMS with an included pre-charge function.

**5. Detailed explanation of Inrush current in RC Charging Circuit.** The figure below shows a capacitor, (C) in series with a resistor, (R) forming a **RC Charging Circuit** connected across a DC battery supply ( $V_s$ ) via a mechanical switch. When the switch is closed, the capacitor will gradually charge up through the resistor until the voltage across it reaches the supply voltage of the battery. The manner in which the capacitor charges up is also shown below. This circuit is a simplified representation of a real battery-inverter circuit during initial cold start with the capacitor representing the inverter and the resistor representing all combined resistances, including battery internal resistance with the BMS, cables, switch, fuse, etc.



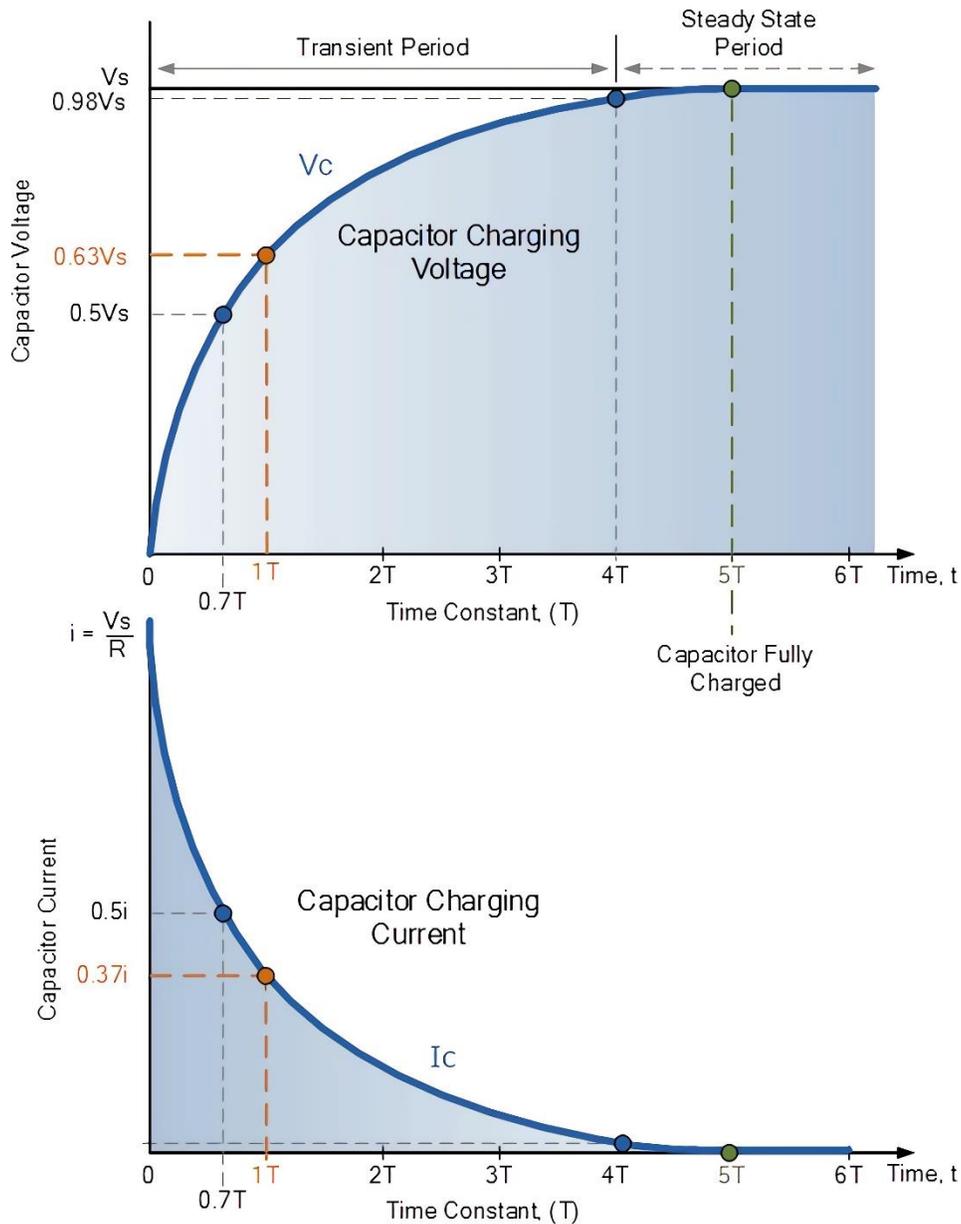
Let us assume above, that the capacitor, C is fully "discharged", and the switch (S) is fully open. These are the initial conditions of the circuit, then  $t = 0$ ,  $i = 0$  and  $q = 0$ . When the switch is closed the time begins at  $t = 0$  and current begins to flow into the capacitor via the resistor.

Since the initial voltage across the capacitor is zero, ( $V_c = 0$ ) the capacitor appears to be a short circuit to the external circuit and the maximum current flows through the circuit restricted only by the resistor R. Then by using Kirchhoff's voltage law (KVL), the voltage drops around the circuit are given as:

$$V_S - R \times i(t) - V_C(t) = 0$$

The current now flowing around the circuit is called the **Charging Current** and is found by using Ohms law as:  $i = V_S/R$ .

### RC Charging Circuit Curves



The capacitor now starts to charge up as shown, with the rise in the RC charging curve steeper at the beginning because the charging rate is fastest at the start and then tapers off as the capacitor takes on additional charge at a slower rate.

As the capacitor charges up, the potential difference across its plates slowly increases with the actual time taken for the charge on the capacitor to reach 63% of its maximum possible voltage, in our curve  $0.63V_S$  being known as one Time Constant,  $(T)$ .

This 0.63Vs voltage point is given the abbreviation of 1T, (one time constant).

The capacitor continues charging up and the voltage difference between Vs and Vc reduces, so too does the circuit current, i. Then at its final condition greater than five-time constants (5T) when the capacitor is said to be fully charged,  $t = \infty$ ,  $i = 0$ ,  $q = Q = CV$ . Then at infinity the current diminishes to zero, the capacitor acts like an open circuit condition therefore, the voltage drop is entirely across the capacitor.

So mathematically we can say that the time required for a capacitor to charge up to one time constant, (1T) is given as **RC Time Constant, Tau**

$$\tau \equiv R \times C$$

This RC time constant only specifies a rate of charge where, R is in  $\Omega$  and C in Farads.

Since voltage V is related to charge on a capacitor given by the equation,  $V_c = Q/C$ , the voltage across the value of the voltage across the capacitor (Vc) at any instant in time during the charging period is given as:

$$V_C = V_S (1 - e^{(-t/RC)})$$

Where:

- Vc is the voltage across the capacitor
- Vs is the supply voltage
- t is the elapsed time since the application of the supply voltage
- RC is the *time constant* of the RC charging circuit

Time Constant	RC Value	Percentage of Maximum	
		Voltage	Current
0.5 time constant	0.5T = 0.5RC	39.3%	60.7%
0.7 time constant	0.7T = 0.7RC	50.3%	49.7%
1.0 time constant	1T = 1RC	63.2%	36.8%
2.0 time constants	2T = 2RC	86.5%	13.5%
3.0 time constants	3T = 3RC	95.0%	5.0%
4.0 time constants	4T = 4RC	98.2%	1.8%
5.0 time constants	5T = 5RC	99.3%	0.7%

After a time period equivalent to 4 time constants, (4T) the capacitor in this RC charging circuit is virtually fully charged and the voltage across the capacitor is now approximately 98% of its maximum value, 0.98Vs. The time period taken for the capacitor to reach this 4T point is known as the **Transient Period**.

After a time of 5T the capacitor is now fully charged and the voltage across the capacitor, (Vc) is equal to the supply voltage, (Vs). As the capacitor is fully charged no more current flows in the circuit. The time period after this 5T point is known as the **Steady State Period**.

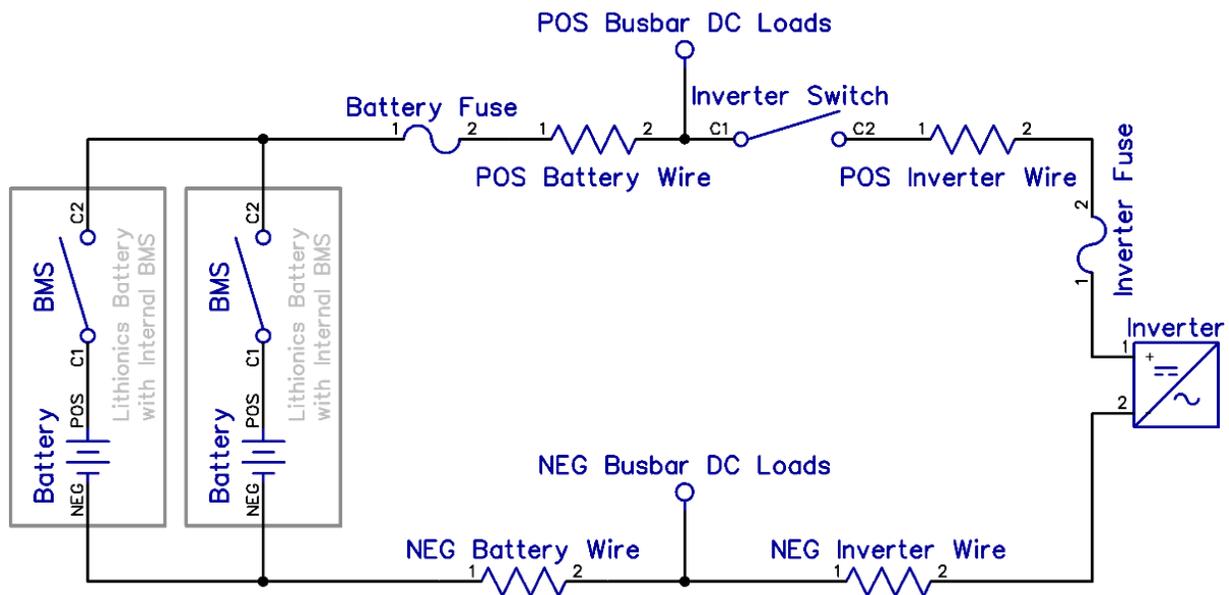
Then we can show in the table above the percentage voltage and current values for the

capacitor in a RC charging circuit for a given time constant.

Note that as the charging curve for a RC charging circuit is exponential, the capacitor in reality never becomes 100% fully charged due to the energy stored in the capacitor. So for all practical purposes, after five time constants a capacitor is considered to be fully charged.

**6. Inverter Inrush Period, Switching Speed and Sequence.** In practical terms we only care about inrush peak current and how fast it drops below critical level. This is where the subject of switching speed, switching devices, and switching sequence becomes important. In most cases the critical portion of inrush is finished by the time  $1T$ , which is typically in the range of 0.2ms to 1.0ms. The switching device which initiates inverter cold start can be a mechanical switch, such as a typical rotary switch used in motorhomes to disconnect house batteries, or a solid-state switch, such as the MOSFET transistors inside the internal BMS when the battery's ON/OFF button is used to enable battery power. This premium function is included in all Lithionics batteries, but it has an inherent limitation of switching speed imposed by the nature of the MOSFET transistors used in Internal BMS batteries. It takes about 0.2ms for the MOSFETs to go from open circuit to closed circuit state, during which time the MOSFETs resistance is moving from very high to very low, but during this period of partial resistance there is a lot of stress on the internal silicon structure due to instant heat rise and not enough time to dissipate it. As such, using an Internal BMS as a power switch during inverter cold start imposes maximum stress on the BMS and if the peak inrush current is high enough, it could damage the BMS. It also means that a mechanical switch should be the preferred method of inverter cold start where possible and use of high-quality switches capable of high inrush is also important. The example schematic below demonstrates a series connection of a BMS switch and a mechanical switch. When 2 switches are in a series connection, the last switch closing operation is the one initiating the inrush current, so the preferred sequence is to turn the battery on while the mechanical inverter switch is open and then close the mechanical inverter switch.

**7. Inverter Inrush Circuit Example.** The below circuit shows typical DC power wiring components in a motorhome and a table of their respective resistance values. When dealing with very low resistance, each wire's resistance becomes important to account for, so the circuit shows wire segments as resistors, to visualize their contribution to the total circuit resistance. The example is shown with 2 parallel batteries since the resistance calculation and switching sequence becomes more complex with multiple batteries.



Components	Resistance (mOhm)
Lithionics 315AH Battery w/BMS	2.1
Battery Fuse 300A	0.15
Positive Battery Wire 2ft 2/0	0.25
Inverter Switch	0.05
Positive Inverter Wire 2ft 2/0	0.25
Inverter Fuse 300A	0.15
Inverter Xantrex XC 3000	2.26
Negative Inverter Wire 2ft 2/0	0.25
Negative Battery Wire 2ft 2/0	0.25
<b>Total Circuit Resistance (mOhm)</b>	<b>5.71</b>
<b>Peak inrush current at 13.5V (A)</b>	<b>2364</b>
<b>Inrush RC time constant 1T (ms)</b>	<b>0.28</b>

Popular Inverter Models	Resistance (mOhm)	Capacitance (F)
Xantrex XC 2000W	3.35	0.0252
Xantrex XC 3000W	2.26	0.0495
Victron Multiplus 3000W	1.65	0.18
Victron Quattro 5000W	0.76	0.468

**8. Inverter inrush with parallel batteries.** Consider the system with 2 parallel batteries as shown above. If the inverter switch is closed, while both battery switches are open, then the first battery being turned on would force its internal MOSFETs switch to handle the entire inrush current, putting maximum stress on that battery. But if the inverter switch is open and both batteries are turned on first, then closing the inverter switch handles entire inrush current, while the two batteries split the current equally, cutting individual battery peak inrush in half. At that time the MOSFETs in both batteries are already fully conducting with lowest resistance, so there is even less stress on them. Therefore, correct cold start sequence is important to reduce the stress on the BMSs, and especially important in systems with multiple parallel batteries. Smaller batteries, such as Lithionics 130Ah Group 31 batteries have a lesser BMS inrush rating of 1,200A and a slightly higher resistance of 3.5 mOhm, so when multiple batteries are in parallel the inverter switch operation sequence becomes critical as a single battery can't handle the entire inrush current, but multiple parallel batteries all turned on prior to closing the inverter switch would handle it easily.

**9. Battery improvements to better handle Inverter Inrush.** Lithionics Battery engineers are making continuous hardware and firmware improvements to the BMS design as larger inverters become more popular in motorhomes and customer's power needs continue to grow. At the end of 2021 an improvement was developed and deployed in a battery firmware release to reduce the risk of inrush related damage, but the minimum resistance requirement still applies for correct system operation. Another small improvement was done in the BMS hardware design to break up the inrush period into shorter pulses, which reduces the risk of damage when coupled with Victron inverters, which have much larger capacitance and longer inrush time period. However, this only addresses the time element of inrush, managing the peak current based on circuit resistance is still needed in the overall system design.

When planning your system with Lithionics Batteries please consult with Lithionics Installation guides and specifications to make sure your system is designed correctly, using the best choice of Internal or External BMS to fit your power needs. All guides and support documents can be found on the Lithionics Battery Web site Support page here <https://lithionicsbattery.com/support/>

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