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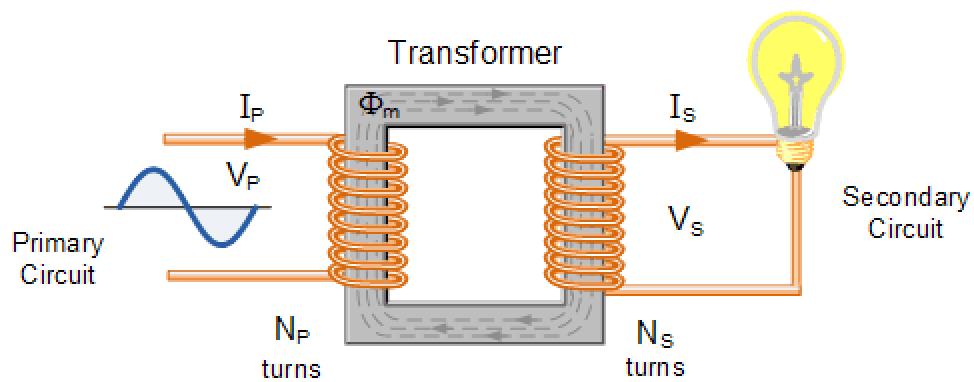
# Transformer Inrush. What? Why? Who cares?

If you have taken a tech call, or spent any time near someone who has, you may have heard of the infamous "transformer Inrush". If you would like to understand what that is and why it causes so many tech calls, keep reading! If not, too bad you already opened the FAQ and now you must read the whole thing! 😊

## What is transformer Inrush?

To understand transformer inrush, you first need a basic understanding of how transformers "transform" AC voltages. Here is a picture of an isolation transformer being used to change the source voltage to a voltage suitable for a light bulb:




In this picture, an AC voltage (Vp) is applied across the coil on the primary side of the transformer. This causes a current (Ip) to flow through the turns of the coil. A current in a wire will always create a magnetic field perpendicular to its direction of flow. In a transformer, the orientation of the turns amplifies this magnetic field. The flow of this magnetic field is called "flux". The number of turns can be adjusted to change the total magnetic flux in the transformer. Too much flux can cause the transformer to "saturate" which is the term used to describe when a transformer is magnetic flux is too high for the size of the core. When at transformer is "saturated" it loses its ability to transfer energy to the secondary effectively, usually causing excess heating. If there is too little magnetic flux, the transformer will not be able to support the output voltage that is expected and the lightbulb in the above picture will dim. Too little magnetic flux is what causes poor regulation in chargers. At high loads, the transformer does not have enough energy stored as flux to keep the output voltage high enough.

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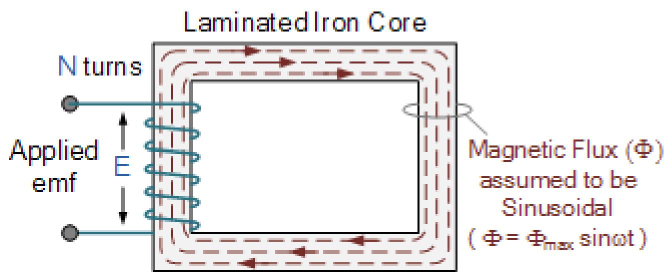
Here is a picture of what the magnetic flux looks like in a transformer:




The flux shown above rotates through the core as shown by the directional arrows. When turns are added as a secondary winding, like the light bulb picture from before, the flux is converted back to current. This is called "mutual induction". The turns ratio determines the voltage on the secondary winding. If there are half as many turns on the secondary as the primary, the induced voltage will also be half. It is important to note that transformers only work with alternating currents (AC). They will not work with direct current (DC) applications because the constant current in one direction saturates the transformer and does not allow for mutual induction.

## Okay, I understand transformer flux now. What does that have to do with inrush?

In short, everything. For a transformer to work correctly, it needs to be "energized". When voltage is applied to a transformer winding, there is an "inrush" in current to the transformer to "energize" the core and create the flux that was previous discussed. This inrush of current happens in a fraction of a second, typically 2-3 milliseconds, and the amount of current required is proportional to the size of the core, the number of turns on the winding, and the instantaneous voltage at the time of energizing.

## Why is inrush current an important design consideration? Why does it matter if there is a short surge of current?

The answer to this question has everything to do with breakers. Confused? That is what this FAQ is for! Circuit breakers "trip" in one of two ways:

1. When a current is applied through the breaker that is higher than its rated current, internal components of the breaker overheat. This heat is monitored and when it exceeds an expected value, the breaker opens. This process is very slow. It can take hours to trip a breaker that is slightly overloaded.

2. When an exceptionally high current is detected, like a short, the breaker opens. This high current is detected using the same ideas that the transformer depends on. The high spike of current generates a strong magnetic field and the breaker's components detect this spike (almost) instantaneously.

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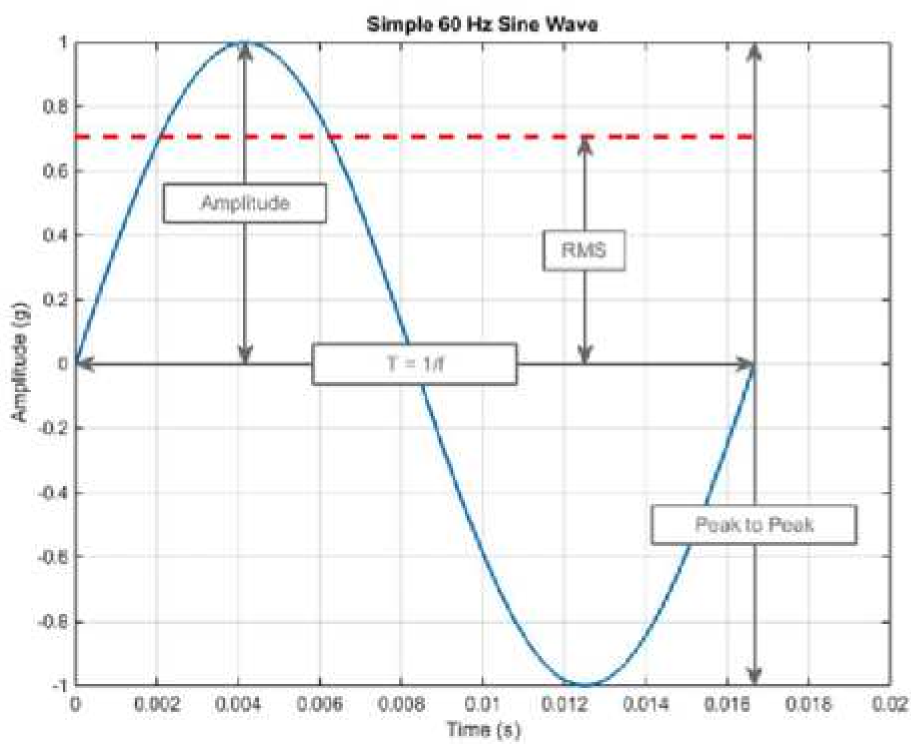
At this point, you may have already figured out the problem. If a transformer has a very high inrush spike, the breaker open because of the magnetic field that current creates. This could cause a situation where a charger loses AC power, and when that power comes back the input breaker opens because of an inrush, leaving the charger unpowered until someone can manually reset the breaker. If that charger is located somewhere far away, or just not monitored well, the batteries can go uncharged for an unknown amount of time.

## Sometimes the breaker opens because of inrush and sometimes it does not. Why is the inrush current so random?

Inrush may seem random, but it is very repeatable. As previously mentioned, the total inrush is proportional to the size of the core of the transformer, the amount of turns on the winding being powered, and the instantaneous voltage at the time of energizing. Its that last part that is important. The size and turns on the transformer are not changing, but the voltage is. Here is a picture of a typical 60Hz sine wave:



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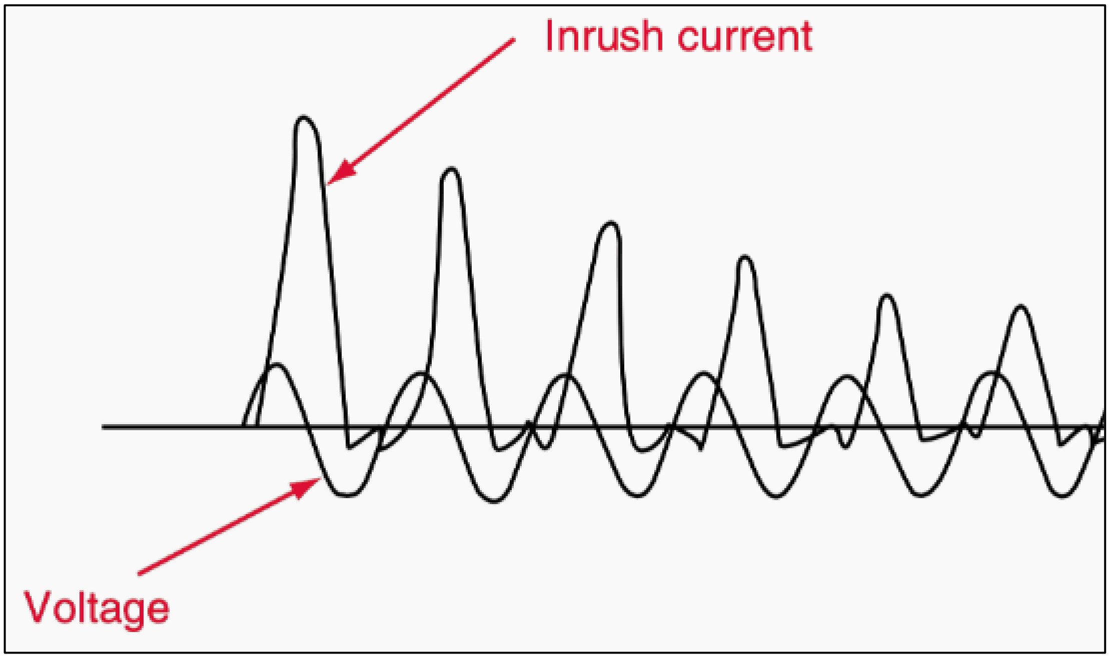
Energizing the core of the transformer happens in just a few milliseconds. As you can see in the 60Hz sine wave, voltage varies from 100% to zero every 8.66 milliseconds. That means that the voltage applied to the primary to energize the transformer changes very quickly, too quickly to perfectly repeat by hand, so every time the transformer is turned on, it is at a different voltage level. If the transformer happens to be energized at the peak of the AC waveform, the inrush current is very low. The amount of energy required to energize the core stays the same which means that higher voltages will require less current. The worse inrush happens when the AC waveform is crossing zero. At this moment, the voltage levels are extremely low, requiring a lot of current to energize the core. Here is a picture of what inrush looks like over time:




## Why do some customers have issues with inrush and others do not? It is the same design, so they should have the same inrush, right?

It is correct to say that the power required to energize the transformer is the same in chargers of the same design, but there is another important thing to consider. A transformer does not get the current it wants just because it asks for it. If a transformer is connected to a very high impedance source, a source that is unable to supply high current changes quickly, the source will provide as much current as it can. The time it takes to energize the transformer will take longer, but the magnitude of the inrush spike will be lower. This is reflected in the wide inrush range that is calculated for each transformer. A transformer will have a "typical" inrush current based on typical source impedances. It will also have a "theoretical max" inrush current that is THREE TIMES HIGHER! That means that a design with a typical inrush of 500A could potentially have an inrush spike of 1500A if the source impedance is very low. Most customers will not run into this issue if the transformer is designed well, but some customers with very low impedance sources will consistently have trouble addressing this inrush issue.

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# What can we do reduce inrush and keep breakers from tripping?

The first step is a good transformer design. Here are a few key things to keep in mind to reduce inrush when designing a transformer:

1. Do not oversize the core. Larger transformers will run cooler and regulate better, but they also cost much more, and the inrush is much higher. Try to keep the core as small as possible without overheating or losing regulation.

2. If possible, move the primary windings to the outer layer of the coil. The farther the primary is from the core, the less it induces flux on the core. This will barely affect the normal operation of the transformer, but it will cut the inrush current by a lot. Typically, transformers with primaries on the outer layers are HALF the inrush of transformers with the primary close to the core. It takes longer to energize the core, but that's a good thing.

3. Keep the number of primary turns high. Each turn amplifies the power transfer from the winding to the core, so more turns mean less inrush. Think of it like filling a pool with buckets of water. It is easier to fill a pool with buckets of water if you have a group of people all filling it at the same time rather than one person.

There are things a customer can do to keep their inrush low as well. Here are some ideas:

1. Size the charger according to what is needed. If a larger charger is purchased, it can power loads at a lower current by setting the current limit lower, but the inrush is always the same. That means that running a charger at lower loads does not change the inrush. Purchasing an 800A charger and using for 100A loads is a bad idea.

2. Increase the source impedance. As mentioned before, the source impedance is a critical factor in determining the inrush of a transformer. There are many times where power generation plants purchase chargers and have inrush issues. This is because their source impedance is extremely low. There is nothing that we can do to the design of a transformer to keep the inrush low enough if the source impedance is too low. Remember, the theoretical max inrush can be 3 times higher than the typical. The breakers we use are the slowest version available, and they typically only allow for about 50% higher than the typical inrush. For example, a transformer with a typical inrush of 500A would have a breaker that opens if the inrush hits 750A or so, and the theoretical max inrush with a low impedance source could be 1500A!

3. Ensure that the customer is feeding the charger with a breaker that has a slow trip response capable of lasting through inrush. Most breakers are not designed for large inrush spikes. Most inrush issues result from customers purchasing the wrong type of source breaker.

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