Transformer Inrush Currents and Protection

Overview

When a transformer is energized, it tends to draw a high magnitude transient current from the supply which can be typically many times the normal full load current approaching 12 times nominal or even higher (dependant on total system characteristics) which can cause nuisance tripping of the input over-current protection. This inrush current is unipolar in nature and rises abruptly in the first half cycle to its maximum value and then decays exponentially until the normal steady-state magnetizing conditions are reached usually within 100 milliseconds. It should be noted that this phenomenon is not limited to transformers but is common to any AC powered electromagnetic device such as AC Motors, etc. Inrush currents may also be generated by other devices such as equipment with electronic power supplies, incandescent lamps etc. but for different reasons and not covered by this paper. Note that certain loads connected as a load on the transformer output and may also contribute to the input inrush current.

A typical idealized waveform of a transformer inrush current is illustrated in the figure below which shows the inrush current in terms of magnitude times nominal against power cycles for one phase with a superimposed oscillograph of a three phase transformer during energization.

The inrush current is a result of the falloff of self-inductance of the magnetic core of the transformer caused by its magnetic flux saturation during the initial transient power-on conditions and prior to the establishment of steady state operating conditions with its magnitude influenced by a number of factors discussed following. This phenomenon may be more pronounced for higher efficiency transformers due to $B-H$ loop characteristics of the higher grade core steels coupled with more efficient core geometries employed to reduce transformer losses and for low leakage transformers (< 3%).

Putting the phenomena into perspective (and assuming a low feeder impedance of about 1%), standard transformer inrush currents are typically in the range of 8 – 12 times nominal current but may be as high as 10 – 20 times (manufacturer/type specific) and about 6 – 8 times for low inrush models but note the key qualifier ‘typical’.
The Causes and Influences of Inrush Currents

The inrush current phenomenon is a direct result of flux saturation of the magnetic core during initial power on which causes the self-inductance of the transformer coil to fall off to a very low value resulting in large currents driven by the input excitation voltage. This phenomenon occurs only during the initial transitory power-on conditions until steady state conditions are established usually in about 1/10 of a second. When flux balance is established the magnetic flux is symmetrically balanced about zero in all legs of the transformer core and the self-inductance returns to a high steady state value with the transformer drawing only a small magnetizing current (typically < 0.5 - 2 % of full load).

The magnitude and duration of the inrush current depends upon the following:

- Impedance of the upstream supply circuit
  
  *Upstream transformer impedance plus line feeder impedances*

- Leakage impedance of the Transformer
  
  *Primary winding resistance and the inductive leakage impedance to the core (not the primary/secondary leakage).*

  **Note:** Low leakage impedance transformers will produce high inrush currents

- Point on the voltage wave at the instant the transformer is energized (i.e. switching angle)
  
  *A random phenomenon that the user has no control over in 3-phase systems*

- The B-H Loop characteristic of the core steel coupled with the core geometry
  
  *High efficiency transformers with higher grade steels and more efficient core topologies tend to generate higher inrush currents due to its squarer B-H loop characteristics*

- Magnitude and sign of the residual flux (remnant magnetism) in the core from the prior power down
  
  *A random phenomenon that the user has little control over but may be addressed in specific applications using an RC network in the input or output circuit that can potentially 'ring out' the residual flux*

- Transformer characteristics, defined by its design parameters, will influence the magnitude of inrush
  
  *Transformers with lower inrush currents can usually be specifically designed by the manufacturer but with compromises; e.g. impedance, cost, losses, etc. (see section on low inrush transformers)*

- The L/R ratio of the time constant of the system will control the duration with a higher resistance versus inductance leading to quicker stability

  **Note:** As a rule of thumb smaller transformers < 500kVA will generally achieve steady state in about 100ms or less with large multi-MVA units requiring up to 1 second or more

Low Inrush Current Transformers

Transformers can be designed for reduced inrush current characteristics by tweaking some of the variables in the design process but this requires certain compromises and inevitably a higher cost. Some factors that contribute to reducing the inrush current are:

- Lower operating flux density reduces inrush
  
  *Typically larger core and/or more turns*

- Leakage Impedance
  
  *Leakage of primary winding to core not just impedance defined by the primary/secondary leakage*

- Large primary winding area
  
  *Position in winding, layers and air ducts*

- Relative number of conductor turns and relative core size

- Core magnetic properties and its geometry

- Winding geometries

Note that Aluminum transformers tend to have lower inrush currents due to their larger winding geometries, higher resistance with more turns and a smaller core for a given kVA (essentially resulting in higher leakage impedance).
Application Solutions

A general approach to the problem of dealing with transformer inrush currents is both to select the appropriate transformer for the application and to choose an input over-current protection device with the right time delay characteristic to avoid nuisance tripping coupled with appropriate over-sizing the input protection.

The National Electric Code (NEC)* addresses the inrush current issue by allowing for input protection up to 250% overcurrent when coupled with secondary circuit protection at 125% of nominal overcurrent rating (per 450.3). The conductors also require protection (per 240.4) which at first glance would require significant over sizing of the primary conductors to match the increase overcurrent protection. However, under certain conditions the Tap rule (per 240.21) may apply and the primary conductors may not need to be oversized to match the increased primary overcurrent protection allowing the input wires to the transformer to be sized smaller than the normal overcurrent and conductor sizing.

*Note that primary only protection is only for a specific category of transformer and is not generally applicable to 3-phase distribution transformers and hence not considered here (NEC 240.21 (C) (1)).

The proposed approach is detailed below:

- Avoid using transformers with low leakage impedances i.e. below 3.1% as these may be extremely difficult to successfully apply without nuisance tripping
  Transformers with higher leakage impedances will inevitably have lower inrush currents but there are practical limits such as regulation, distortion, sags due load switching, etc.

- Use Breakers with trip mechanisms intended for Motor and Transformer application (usually instantaneous trip of 10 times rated current for one cycle instead of the standard 6 – 8 times) or units with electronic adjustable instantaneous trip levels set at the appropriate levels
  Time-Delay Fuses may also be applied but may be weakened over time and fail when subjected to frequent on and off cycles

- Oversize the input protection in the range of 150 to 200% (or even to 250% if conditions dictate, such as low upstream impedance) of nominal input current coupled with Output Protection rated 125% of nominal output current (See NEC 450.3 & 420.21 (3))
  The over-sizing of the input breaker essentially multiplies the instantaneous overcurrent by the over-sizing ratio. eg. 200% over-sizing will increase the short term percent overcurrent trip from 12.5 x nominal to 20 x nominal (assuming a 125% rated breaker with a 10 x short term trip)

- Use a low inrush transformer where input breaker over-sizing is not possible or desired
  Some applications such as UPS, Static Switches, etc. are sensitive to excessive inrush currents

- For applications where the source itself is sensitive to inrush currents (eg. Generators, AC Inverters, etc.), consider using multiple transformers instead of one with coordinated sequential switching

NEC (2008) References

Note that the following selected NEC references are presented to highlight the allowances made by NEC re over-sizing of the overcurrent protection but is by no means a complete application guide and it is incumbent on the user/installer to be cognisant with all the local electric code requirements related to the installation.

110.52 Overcurrent Protection.

Motor-operated equipment shall be protected from overcurrent in accordance with Parts III, IV, and V of Article 430. Transformers shall be protected from overcurrent in accordance with 450.3.
450.3 Overcurrent Protection

(B) Transformers 600 Volts, Nominal, or Less. Overcurrent protection shall be provided in accordance with Table 450.3(B).

<table>
<thead>
<tr>
<th>Protection Method</th>
<th>Primary Protection</th>
<th>Secondary Protection (See Note 2,)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Currents of 9 Amperees or More</td>
<td>Currents Less Than 9 Amperees</td>
</tr>
<tr>
<td>Primary only protection</td>
<td>125% (See Note 1.)</td>
<td>167%</td>
</tr>
<tr>
<td>Primary and secondary protection</td>
<td>250% (See Note 3.)</td>
<td>250% (See Note 3.)</td>
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Notes:
1. Where 125 percent of this current does not correspond to a standard rating of a fuse or nonadjustable circuit breaker, a higher rating that does not exceed the next higher standard rating shall be permitted.
2. Where secondary overcurrent protection is required, the secondary overcurrent device shall be permitted to consist of not more than six circuit breakers or six sets of fuses grouped in one location. Where multiple overcurrent devices are utilized, the total of all the device ratings shall not exceed the allowed value of a single overcurrent device.
3. A transformer equipped with coordinated thermal overload protection by the manufacturer and arranged to interrupt the primary current shall be permitted to have primary overcurrent protection rated or set at a current value that is not more than six times the rated current of the transformer for transformers having not more than 6 percent impedance and not more than four times the rated current of the transformer for transformers having more than 6 percent but not more than 10 percent impedance.

240.4 Protection of Conductors.

Conductors, other than flexible cords, flexible cables, and fixture wires, shall be protected against overcurrent in accordance with their ampacities specified in 310.15, unless otherwise permitted or required in 240.4(A) through (G).

II. Location.

240.21 Location in Circuit.

Overcurrent protection shall be provided in each ungrounded circuit conductor and shall be located at the point where the conductors receive their supply except as specified in 240.21(A) through (H). Conductors supplied under the provisions of 240.21(A) through (H) shall not supply another conductor except through an overcurrent protective device meeting the requirements of 240.4.

(1) ....

(2) ....

(3) Taps Supplying a Transformer [Primary Plus Secondary Not over 7.5 m (25 ft) Long]. Where the tap conductors supply a transformer and comply with all the following conditions:

1. The conductors supplying the primary of a transformer have an ampacity at least one-third the rating of the overcurrent device protecting the feeder conductors.

2. The conductors supplied by the secondary of the transformer shall have an ampacity that is not less than the value of the primary-to-secondary voltage ratio multiplied by one-third of the rating of the overcurrent device protecting the feeder conductors.

3. The total length of one primary plus one secondary conductor, excluding any portion of the primary conductor that is protected at its ampacity, is not over 7.5 m (25 ft).

4. The primary and secondary conductors are protected from physical damage by being enclosed in an approved raceway or by other approved means.

5. The secondary conductors terminate in a single circuit breaker or set of fuses that limit the load current to not more than the conductor ampacity that is permitted by 310.15.