Transformer Magnetizing Inrush Current Restraint

Some manufacturers of three-phase recloser and breaker controls have recently introduced a transformer magnetizing inrush current restraint feature. Magnetizing inrush restraint prevents overcurrent-protection responses when magnetizing inrush currents occur.

However, the IntelliRupter® PulseCloser® Fault Interrupter's controlled voltage-point-on-wave closing and use of PulseClosing® Technology mitigate the requirements for this feature. This publication explains why transformer magnetizing inrush restraint may be required for three-phase reclosers and breakers, but not for the IntelliRupter fault interrupter.

Background

Substantial transformer magnetizing inrush current occurs because of two related system conditions:

- Load transformers must have appreciable residual magnetism or remnant flux, which occurs by opening a healthy phase at or near a system voltage-zero with no voltage decay.
- The same phase must close at or near a system voltage-zero with a rising voltage that matches the remnant flux polarity.

However, these conditions are only produced by reclosers and breakers tripping and reclosing three-phase. As these devices randomly reclose voltage-point-on-wave, several congruent system conditions must arbitrarily converge to satisfy these circumstances.

Also, magnetizing inrush current behaves more like load current than fault current. Referring to **Figure 1**, Breaker 1 experiences the cumulative magnetizing inrush current of the feeder, or IM1 + IM2 + IM3 + IM4. However, each downstream fault interrupter (2, 3, and 4) experiences less and less magnetizing inrush current.

S&C Information Bulletin 210-110, "Selection Guide for Transformer Primary Fuses in Medium- and High-Voltage Utility and Industrial Substations," is an excellent resource for understanding the factors involved in selecting the proper protection for medium-voltage transformers. But equally important, it explains how transformer magnetizing inrush currents translate into transformer full-load current multipliers or factors at 0.01 and 0.1 seconds.[1]

Information Bulletin 210-110 also provides charts that show 0.01- and 0.1-second reductions in full-load current factors based on transformer full-load-to-available-fault-current ratios. When this ratio is 0.00, it indicates the transformer is close to a strong source, such as the substation. Higher ratios indicate a weaker source, or the transformer is further from the substation.

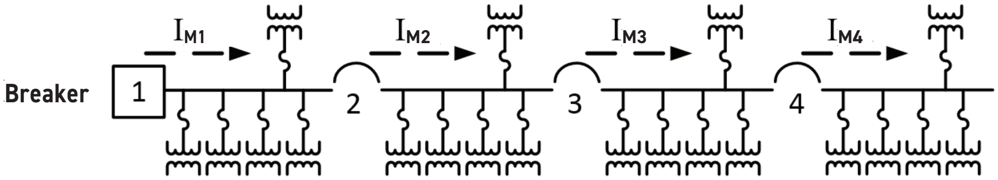

Figure 1. Magnetizing inrush current is cumulative. In this example, Breaker 1 experiences the sum of the magnetizing inrush currents IM1, IM2, IM3 and IM4.

So, a 100-kVA transformer with a full-load-to-fault-current ratio of 0.00 would generate magnetizing inrush currents equivalent to 25 times its full-load current at 0.01 seconds, and 12 times its full-load current at 0.1 seconds. However, when this full-load-to-fault-current ratio is 0.04, full-load current multipliers drop to nine times full-load current at 0.01 seconds and five times full-load current at 0.1 seconds.

Consequently, breakers and reclosers near the substation are more likely to benefit from magnetizing inrush current restraint, preventing overcurrent-protection responses. This is true because they sense the magnetizing inrush current of their feeder segment and all downstream segments. Moreover, magnetizing inrush current is highest in their feeder segments because of lower full-load-to-fault-current ratios.

Creating Transformer Residual Magnetism or Remnant Flux

Significant transformer residual magnetism or remnant flux is produced by opening a healthy phase at or near a system voltage-zero. But the highest remnant flux results when phase voltage immediately drops to zero volts upon opening.

The polarity of this remnant flux will be determined by the polarity of the falling voltage before opening at a voltage-zero. By convention, this means remnant flux is negative when the voltage-zero is 0 degrees and positive if the voltage-zero is 180 degrees.

For example, **Figure 2** shows balanced A-, B- and C-phase voltages with the dashed line representing the A-phase voltage. All three phases open simultaneously, but A phase opens at 0 degrees with a falling negative voltage and no voltage decay. Therefore, the remnant flux produced by the A-phase voltage will be negative because the falling voltage was negative before A phase opened at 0 degrees.

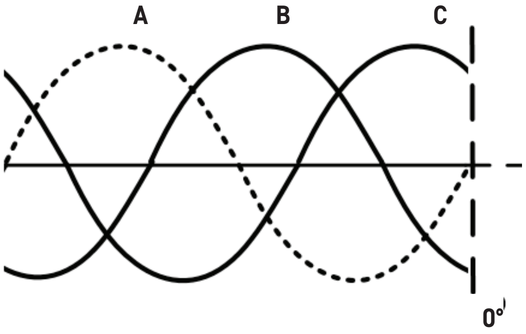

Figure 2. A-phase voltage (dashed line) produces negative remnant flux in downstream A-phase load transformers because it opens at 0 degrees with a falling negative voltage.

The greatest probability of opening a healthy, or unfaulted, phase at or near a voltage-zero is because of three-phase tripping or opening. For example, phase-to-ground faults occur more often than any other fault type. This means when a phase-to-ground fault is cleared, one of the two unfaulted phases has a greater chance of opening at or near a voltage-zero.

However, unlike faulted phases, once a healthy phase opens (even during nonfault events), voltage decay and sub-fundamental frequencies occur that greatly reduce remnant flux. These conditions last a few cycles or longer and result from feeder components, such as motor loads and capacitors, remaining connected after the phase opens.

For example, **Figure 3** shows an A-to-B-phase fault occurs and is cleared in about 5.5 cycles. C phase opens at the same time as A and B phases, but its voltage continues to decay for approximately 170 milliseconds, or roughly 10 cycles on a 60-Hz basis. Additionally, the C-phase voltage waveform also reflects sub-harmonic frequencies during the voltage decay period. Consequently, there is little likelihood downstream C-phase load transformers will have appreciable remnant flux.

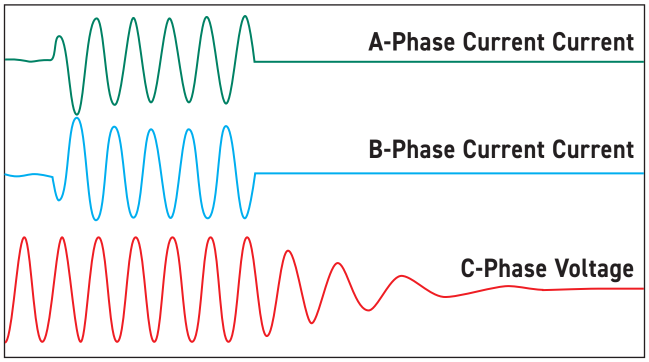

Figure 3. After an A-to-B-phase fault is cleared, C-phase voltage decay with sub-fundamental frequencies greatly reduces remnant flux in C-phase load transformers.

Producing Transformer Magnetizing Inrush Current

Magnetizing inrush currents of concern to phase-overcurrent protection are produced when the polarity of substantial remnant flux is matched by a rising voltage of the same polarity. This means if a healthy phase opens at or near 0 degrees with no voltage decay, it must close at or near 180 degrees and vice versa.

As an example, **Figure 4** shows the balanced A-, B- and C-phase voltages of **Figure 2** with the dashed line again representing the A-phase voltage.

As before, the opening of A phase at 0 degrees produces a maximum negative remnant flux in downstream A-phase load transformers. But as B and C phases open near a voltage peak (240 and 120 degrees respectively), their downstream load transformers will have much less remnant flux.

Figure 4 also indicates all three phases subsequently close simultaneously, but A phase closes at 180 degrees with a rising negative voltage. Because this rising negative A-phase voltage matches the negative remnant flux in downstream A-phase load transformers, this closing action will generate the maximum magnetizing inrush current possible based on transformer full-load-to-available-fault-current ratios.

Conversely, closing with a voltage polarity opposite to that of the remnant flux eliminates magnetizing inrush current completely. Therefore, if A phase in **Figure 4** were to open and close at or near 0 degrees (or 180 degrees), no magnetizing inrush current would occur.

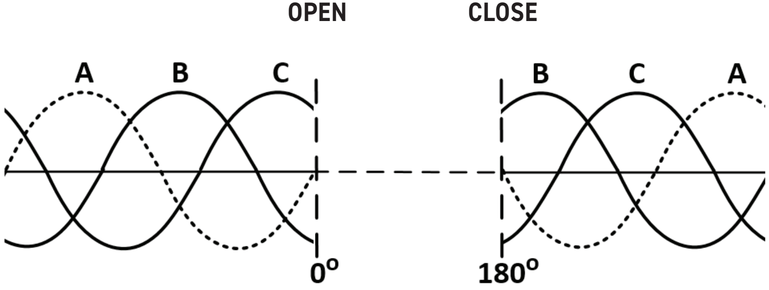

Figure 4. A-phase voltage (dash line) produces negative remnant flux upon opening and maximum magnetizing inrush current upon closing.

Closing at system-voltage peaks significantly lessens magnetizing inrush current. And closing at a voltage peak opposite to the polarity of the remnant flux appreciably reduces magnetizing inrush current.

So, because three-phase reclosers and breakers close at random system-voltage angles, several congruent system conditions must arbitrarily converge to produce protection-level magnetizing inrush currents.

Controlled Voltage-Point-On-Wave Closing

The controlled voltage-point-on-wave closing and PulseClosing operations of the IntelliRupter fault interrupter always occurs at or near a system-voltage peak. Consequently, magnetizing inrush current is always substantially less than what is produced by the random three-phase, voltage-angle closing of a recloser or breaker.

As a reminder, PulseClosing Technology reduces the mechanical energy (I2t) used to test for the continued presence of faults to approximately 5% of what a recloser produces when it repeatedly recloses into a fault. And PulseClosing operations are performed on a phase-by-phase basis starting with the phase that recorded the highest current level.

Phases are tested for fault presence by initiating a single-phase, rapid close-open operation at specific peak system voltage angles. Using conventional vacuum bottle contacts, this rapid close-open operation is initiated after a system voltage peak such that the duration of the resulting minor loop of current is between approximately 0.25 and 0.5 cycles.

This resulting minor loop of current is then analyzed to determine whether it represents a fault condition. If the analysis returns a fault result, a second PulseClosing operation is immediately executed using opposite voltage polarity to what was used for the first PulseClosing operation.

Once a PulseClosing operation has determined there is no fault on a given phase, that phase closes at or near a system voltage peak. This controlled voltage-point-on-wave process further mitigates any unknown or evolving consequences involved in reenergizing a phase.

Additionally, conventional three-phase closing also adheres to this practice. So even if a PulseClosing operation doesn't precede a phase closing, each phase closes sequentially at or near a system voltage peak.

Voltage-Point-On-Wave Closing Mitigates Magnetizing Inrush Current

Presuming an IntelliRupter fault interrupter tripped three-phase because of a transient A-phase-to-ground fault, the continued presence of the fault is tested using a PulseClosing operation. Because this is a controlled voltage-point-on-wave process, each phase is sequentially tested, starting with the phase that recorded the highest current.

The A phase recorded the highest current because it was faulted, so it is tested first. However, using a pulse to test the A phase will not result in a fault declaration because the fault was transient and is no longer present, and there is no appreciable remnant flux in downstream A-phase load transformers.

The reason there is no appreciable remnant flux in downstream A-phase load transformers is the fault depressed the A-phase voltage. And because the A-phase voltage was depressed, appreciable remnant flux cannot be produced in load transformers connected to the A phase.

Because A-phase PulseClosing operation results in a no-fault declaration, the A phase closes at or near a voltage peak, and the test using a pulse advances to the phase with the next highest recorded current.

However, the B or C phase may have opened at a voltage-zero, and one of these phases may have downstream load transformers with remnant flux. Therefore, if the first B- or C-phase PulseClosing operation is executed with a voltage polarity that matches the downstream transformer remnant flux polarity, a fault declaration caused by magnetizing inrush current is possible.

Consequently, if the first pulse is flagged as faulted, a second PulseClosing operation is executed using voltage of opposite polarity to the first. As previously indicated, the application of voltage polarity opposite to that of the remnant flux substantially reduces magnetizing inrush current.

Thus, the resulting current of the second PulseClosing operation no longer reflects a fault condition, and the phase is closed at or near a voltage peak.

Magnetizing Inrush Current Coordination Considerations

Should the IntelliRupter fault interrupter trip or open three-phase (for whatever reason), and a PulseClosing operation precedes its reclosing, protection-level magnetizing inrush current never occurs. And if the IntelliRupter fault interrupter closes without first performing a PulseClosing operation, closing each phase sequentially at or near a system voltage peak substantially reduces protection-level magnetizing inrush currents.

Consequently, any remaining concerns related to magnetizing inrush current are upstream and downstream three-phase events where the IntelliRupter fault interrupter remains closed. These three-phase events are likely to involve:

- Upstream breaker or recloser three-phase tripping and reclosing
- Downstream recloser three-phase tripping and reclosing
- Extended loss of feeder supply

Upstream breaker or recloser three-phase tripping and reclosing

An event where an upstream recloser or breaker trips and the IntelliRupter fault interrupter remains closed might be because of a transient fault between them. Presuming the upstream device uses magnetizing inrush current restraint to prevent tripping for these currents, there is an extremely remote chance the IntelliRupter fault interrupter may trip when the upstream device recloses.

As previously indicated, several three-phase upstream system conditions must arbitrarily converge to produce protection-level magnetizing inrush currents. And as the IntelliRupter fault interrupter is downstream of the recloser or breaker, it experiences less magnetizing inrush current than the upstream device. However, if the IntelliRupter fault interrupter somehow tripped because of the upstream device reclosing, it would simply perform a PulseClosing operation (mitigating any effects of magnetizing inrush current) and then close.

Further, the tripping of the upstream device has already created a MAIFI event caused by the transient fault. Consequently, the unlikely tripping and PulseClosing operation of the IntelliRupter fault interrupter doesn't add to this index, and its load is quickly and automatically restored.

Downstream recloser three-phase tripping and reclosing

A downstream recloser three-phase tripping and reclosing event where the IntelliRupter fault interrupter remains closed is most likely caused by faults downstream of the recloser. However, the probability of this downstream recloser closing and causing the upstream IntelliRupter fault interrupter to trip because of the recloser's magnetizing inrush current is implausible.

Several three-phase system conditions must randomly converge to produce protection-level recloser magnetizing inrush currents. Also, the time-current coordination of the slower upstream IntelliRupter fault interrupter and the faster downstream recloser should always prevent the IntelliRupter fault interrupter from responding to these currents.

This is especially true if the downstream recloser is equipped with magnetizing inrush restraint. The reason for this is magnetizing inrush restraint would enable the recloser to respond faster to lower fault currents. Consequently, if this is the case, magnetizing inrush restraint in downstream devices actually improves time-current coordination with upstream devices.

Extended loss of feeder supply

If a feeder's supply voltage is lost for an extended period and the IntelliRupter fault interrupter remains closed, cold-load pickup is generally of greater concern than magnetizing inrush current. Additionally, the voltage decay associated with the loss of feeder supply will substantially reduce remnant flux for all feeder load transformers. This is so because there are more feeder components contributing to voltage decay, which increases the decay period and further reduces remnant flux.

Therefore, extended loss of feeder supply doesn't present any magnetizing inrush current concerns.

Conclusions

The causes of appreciable magnetizing inrush current outlined in this publication indicate the occurrence of this phenomenon is actually quite rare. This is true because the production of protection-level magnetizing inrush currents requires these specific three-phase tripping and reclosing sequences to randomly align:

- A healthy phase must open at or near a system voltage-zero.
- There must be no voltage decay associated with opening this phase. Therefore, keep in mind that:
  - > A few cycles of voltage decay appreciably reduce remnant flux.
  - > Feeder components virtually ensure voltage decay occurs.
- The same healthy phase that opened at or near 0 degrees (without voltage decay) must close at or near 180 degrees and vice versa.
- Opening and closing a healthy phase at or near the same system voltage-zero produces no magnetizing inrush current.
- Opening a healthy phase at or near a system voltage-zero and closing at a voltage peak substantially reduces protection-level magnetizing inrush current.

Further, magnetizing inrush restraint was proven to more likely benefit substation breakers and three-phase reclosers near the substation bus. As a reminder, magnetizing inrush current is higher closer to the substation because:

- Load transformers produce greater magnetizing inrush current because of lower transformer full-load-to-available-fault-current ratios.
- Breakers and upstream reclosers sense the cumulative magnetizing inrush current of their feeder segment, plus all downstream segments.

Conversely, the IntelliRupter fault interrupter's controlled voltage-point-on-wave PulseClosing operation and closing actions mitigate protection-level magnetizing inrush currents. Consequently, a magnetizing inrush restraint feature is of little or no value because:

- A PulseClosing operation identifies potential magnetizing inrush conditions.
- Once identified, a PulseClosing operation with a voltage of opposite polarity mitigates magnetizing inrush current.
- Sequential (conventional) closing at or near a system voltage peak substantially reduces protection-level magnetizing inrush current.

Finally, should the IntelliRupter fault interrupter be installed amid breakers and reclosers with an active magnetizing inrush restraint element, there are no adverse consequences because:

- Tripping or opening an IntelliRupter fault interrupter automatically invokes magnetizing inrush current mitigation.
- Magnetizing inrush currents caused by upstream three-phase tripping and reclosing produce no unfavorable results.
- Coordination with downstream reclosers, and the lower magnetizing inrush currents they produce, ensure the IntelliRupter fault interrupter will not trip when these currents occur.
- The protracted loss of feeder-supply voltage results in extended voltage decay because of connected feeder components, eliminating magnetizing inrush current concerns.

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