Providing Secure Ground Protection for Electric Arc Furnaces During Inrush Conditions

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INTRODUCTION

The Nucor Steel Berkeley mill produces hot-rolled, cold-rolled, and coated steel coils and beams. The mill is strategically located in the southeastern United States near Charleston, South Carolina. It is one of 20 steel mills that Nucor Steel owns in the United States.

In 2007, Nucor Steel started replacing their electromechanical overcurrent relays to take advantage of more modern multifunction relay (MFR) features. More specifically, the replacement was intended to use the more precise settings, the definite-time function to coordinate with instantaneous functions on downstream devices, and the alarm and trip recording functions of the MFR. Soon after the ground fault protection was enabled on the new relays, Nucor Steel experienced sporadic tripping of their instantaneous ground fault protection on the feeders to their arc furnaces during magnetizing current inrush to the transformer upon energization. The engineering staff at Nucor Steel gathered event reports from the microprocessor-based feeder relay both to diagnose the cause of the tripping and to characterize the inrush current of the electric arc furnace transformer. With this information, they set about to design a relay setting scheme that would remain secure during inrush while not sacrificing sensitivity or speed. This paper reviews the factors affecting magnetizing current inrush on an electric arc furnace transformer and then describes the steps the Nucor Steel engineers took to analyze and solve the problem.

ARRANGEMENT OF THE POWER DISTRIBUTION SYSTEM

Figure 1 shows a one-line diagram of the Nucor Steel Berkeley mill main power distribution system. It is fed from a single 230 kV line from Santee Cooper in South Carolina, which is a state-owned electric and water utility. As seen in Figure 1, there are four main transformers that feed the plant, T-1 through T-4. Each of them is rated as follows:

80/150 MVA
230 kV/34.5 kV
55°C OA/65°C FFA
Z = 9% @ 80 MVA

Each transformer also has an associated 50 Ω resistor in between the transformer neutral and ground to limit the available ground fault current. The available ground fault current depends on the number of transformers in service. The 89-A switch is normally closed so that there are usually three transformers in service and 1,200 A of available ground fault current on Bus 1, which feeds the arc furnaces.

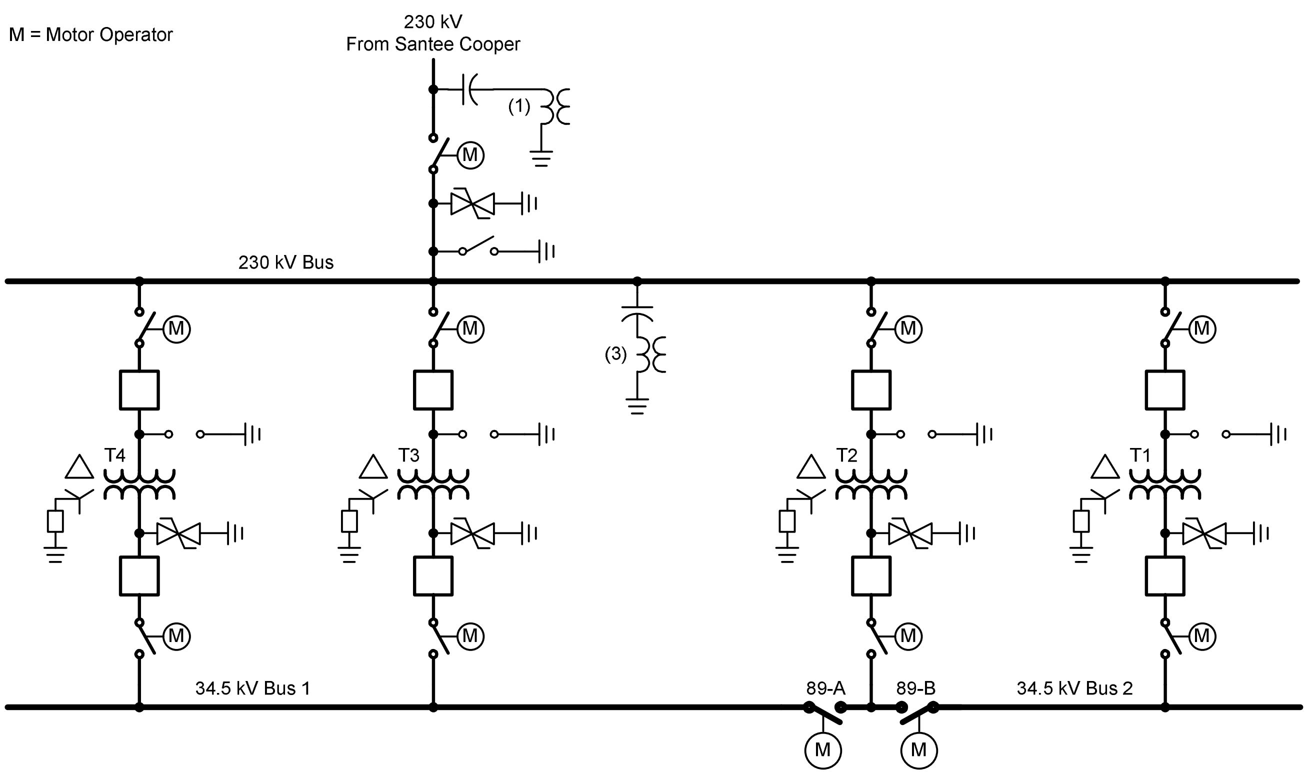

Figure 1. Main power distribution system

An example feeder to one of the arc furnaces is shown in Figure 2. The arc furnace shown in Figure 2 is one of two 140 MW dc arc furnaces. There are also two smaller dual-station, 13.5 MW ladle refining furnaces. The arc furnaces are sized for 165 tapping tons, while carrying a 33-ton heel. They are roughly 25 feet in diameter, with a volume of 6,630 cubic feet.

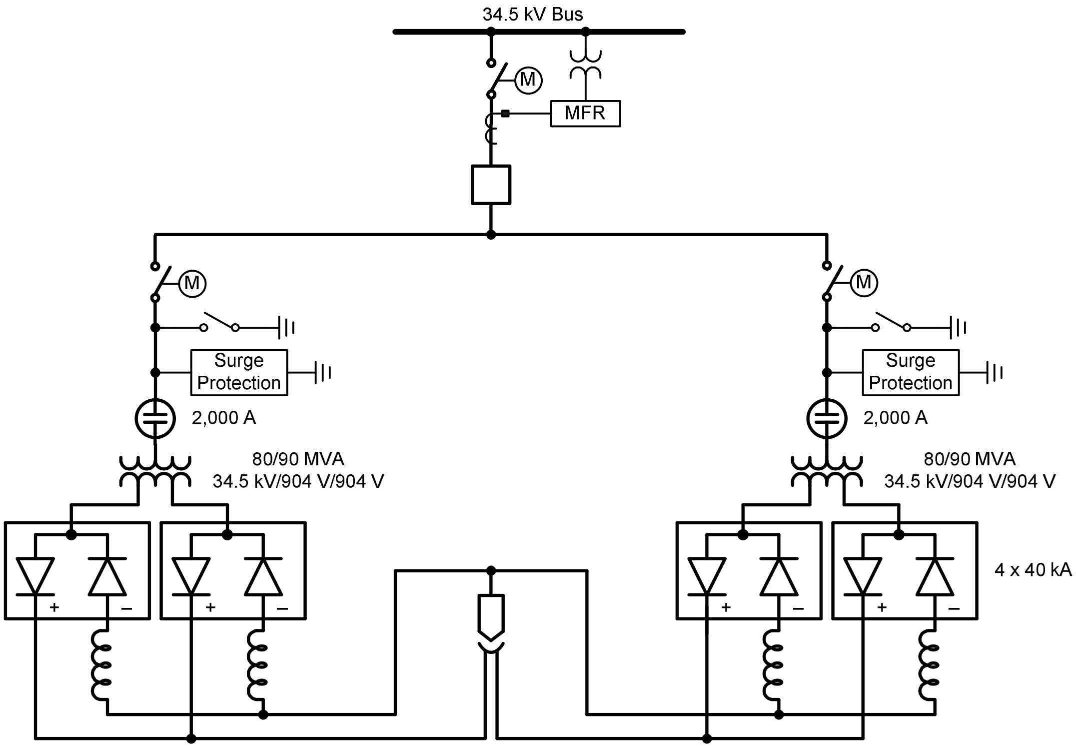

Figure 2. Feeder to the 140 MW arc furnace

A one-line diagram showing protection and tripping logic for the microprocessor-based MFR is shown in Figure 3. The MFR provides both instantaneous (50) and inverse-time (51) phase overcurrent protection from the 3000/5 phase current transformers (CTs). The CT inputs are then tied together to make up a neutral, or residual, connection and run through a 5/15 auxiliary CT to the neutral CT input of the MFR. The MFR then provides instantaneous (50N) and inverse-time (51N) ground overcurrent protection using its neutral current input. The potential transformer (PT) input is used for metering only.

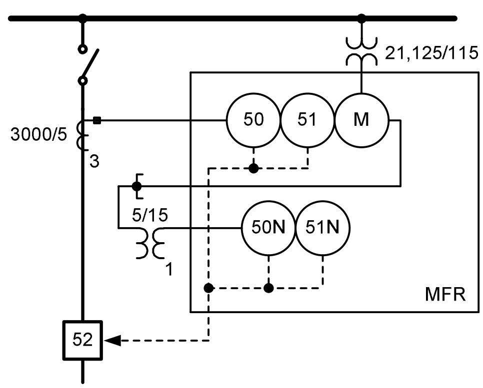

Figure 3. Original MFR design

It should be noted that the MFR is capable of calculating the residual ground current without the aid of the external residual connection and auxiliary CTs; however, these connections existed from a previous electromechanical relay design and were reused with the new MFRs.

TRIP OF THE ARC FURNACE FEEDER ON INRUSH

From July to August 2010, the Nucor Steel Berkeley mill suffered five trips due to magnetizing current inrush on one arc furnace transformer when closing a contactor that feeds the arc furnace. There had been no similar trips on the smaller refining furnaces. An event report for one such trip that occurred on July 16, 2010, is shown in Figure 4. Note that this is a filtered event report and does not show harmonics or dc offset. The relay uses these filtered quantities to perform its protection. Raw event reports that show both harmonics and dc offset are also available from the MFR.

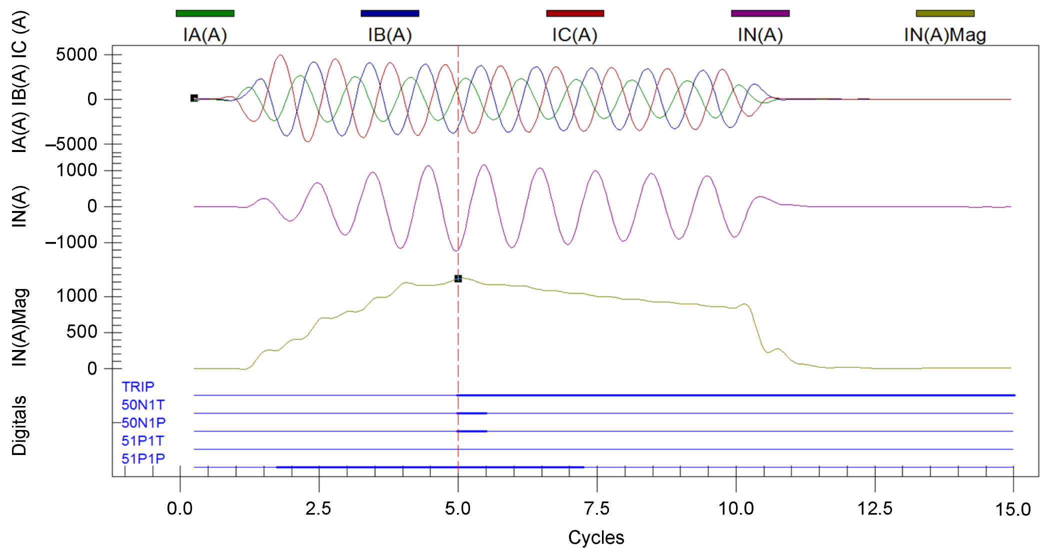

Figure 4. Event report from the July 16, 2010, trip

The event report shows that the ground current, which is the vector sum of the three phase currents, reached a maximum of 1,247 A because of phase unbalance during inrush. The bottom of the report shows that the time-delayed phase overcurrent element (51P1) picked up but did not time out. The relay tripped due to the instantaneous ground overcurrent element (referred to as a neutral element, 50N1, by the relay). At the time, the instantaneous ground overcurrent element was set to 1,200 A primary (6 A secondary) with no intentional time delay. This setting had been raised from an original pickup of 1,000 A to try to prevent nuisance tripping on transformer magnetizing inrush current.

MAGNETIZING INRUSH CURRENT OF AN ELECTRIC ARC FURNACE TRANSFORMER

An electric arc furnace transformer experiences a magnetizing inrush current upon energization that is similar to any other transformer.

Maximum current inrush on a transformer is caused whenever the residual flux in the transformer is a maximum of one polarity and, when energizing the device at a voltage zero crossing, the normally required value of steady-state flux is a maximum of the opposite polarity.[1] This is shown in Figure 5. Note also that if the transformer is energized at the point where the steady-state flux value equals the residual flux value, no transient flux is present and there is no magnetizing inrush current.

It is easily seen that this effect is highly random and dependent on where on the sine wave the transformer is de-energized and then re-energized. Many operations can take place before a worst-case magnetizing current inrush is experienced. With the regular switching that occurs in an arc furnace, it becomes more likely that the worst-case inrush will be experienced.

The sine wave switching phenomenon shown in Figure 5 not only impacts the magnitude of the inrush current but its waveshape as well. Magnetizing inrush current waves have various waveshapes. A typical wave appears as a rectified half wave with decaying peaks. As shown in Figure 5, inrush current begins to flow when the device core saturates. This inrush current is limited only by the system impedance and the impedance the coil would have with the core removed. This results in waveforms that have varying amounts of harmonic distortion according to the amount of residual flux in the transformer and where on the voltage sine wave the transformer is energized.

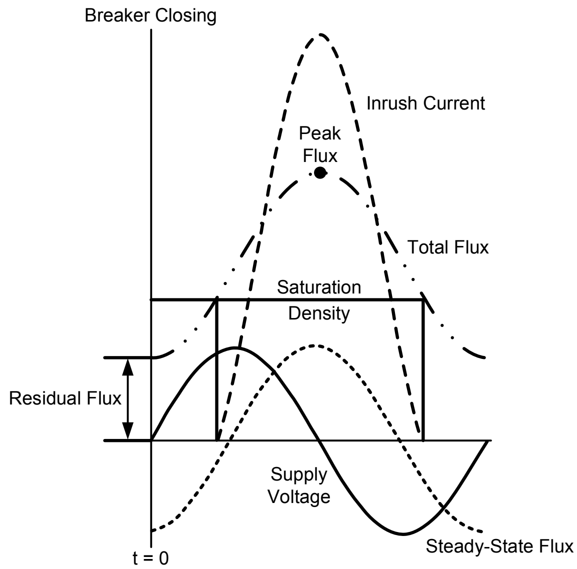

Figure 5. Arc furnace inrush with respect to supply voltage and flux

STEPS TAKEN TO CHARACTERIZE ARC FURNACE INRUSH

The engineers at Nucor Steel Berkeley took steps to characterize the inrush current on the arc furnace transformer feeders. They wanted to better understand the nature of the inrush currents both in terms of magnitude and decay. Nucor Steel engineers used this information to develop relay settings that would be both sensitive and secure. The event reporting function of the microprocessor-based MFR was an ideal tool to perform their analysis. First, Nucor Steel engineers removed 50N from the trip logic to prevent unintended operations during data collection. Second, an event report was triggered whenever the ground current (IN) exceeded 100 A. Fifteen event reports were collected over a two-week period in October 2010. The worst-case event report is shown in Figure 6. This filtered event report shows a ground current that peaks at around 525 A, which is higher than the desired sensitivity of the ground fault protection (400 A).

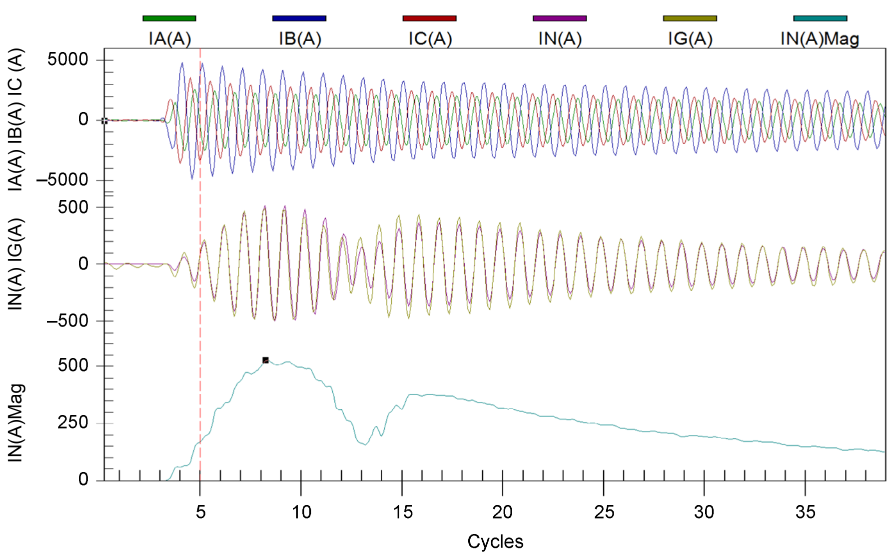

Figure 6. Event report showing arc furnace inrush

The current IN is from the residually connected CTs and is the sum of the secondary current of the phase CTs increased by the 5/15 turns ratio of the auxiliary CT. The arc furnace inrush current has both a dc component and ac magnitudes that vary between phases, as described in the "Inrush on an Electric Arc Furnace" section. This causes the CTs to behave differently from one another and results in a false residual current, as seen in Figure 4 and Figure 6. This residual current is considered to be false because it does not represent the actual ground current but rather the sum of the CT error currents from the three-phase CTs. As stated in IEEE C37.91-2000[2], "instantaneous overcurrent relays may be used, but sensitive settings will probably result in incorrect operations from dissimilar CT saturation and magnetizing inrush. This can be avoided by using a short-time overcurrent relay with a sensitive setting." It is recommended that a suitable time delay for overcoming this effect be determined by multiplying the expected decay time of the dc offset (3 to 5 X/R time constants) by 1.5.[3] This decay of the false residual current can be observed in the event report shown in Figure 6.

Note that although raw event reports were not retrieved and saved from the relays, they can prove to be a valuable forensic tool. Raw event report currents may have demonstrated the characteristic shark fin shape that is typical of CT saturation, along with the dc offset that may have caused it (as shown in Figure 7),[4] whereas the filtered event reports would not provide this. Additionally, with a raw event report, it would be possible to quantify the harmonic content of the inrush current.

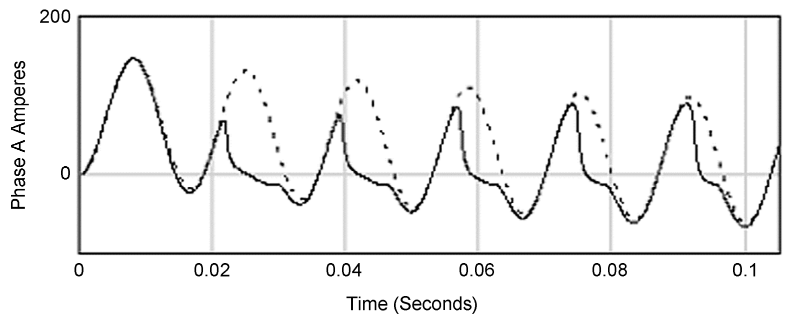

Figure 7. CT secondary current of a saturated CT with dc offset

SETTING METHODS

Traditionally, the following three different methods are commonly used to make instantaneous overcurrent (50) relays secure from unintended operation on inrush:

1. Raise the pickup setting to be above the magnitude of the inrush current.
2. Include a definite-time delay to ride through current inrush.
3. Disable instantaneous tripping and use only inverse-time overcurrent (51) elements.

Note that another less common method of securing the instantaneous overcurrent element is harmonic blocking. This is typically available in transformer current differential relays and may be available in some overcurrent relays. This method was not available in the applied relay and could not be considered.

Method 3 was deemed undesirable by the engineers at Nucor Steel Berkeley because of the sacrifice in speed and accompanying damage that may result. The engineers had originally tried to apply Method 1. They increased the trip to the maximum available ground fault current of 1,200 A and still experienced an unintended operation. This obviously was not acceptable.

Method 2 was applied in the final solution. Based on the interpretation of recorded trips, an instantaneous element was set with a pickup of 5 A (1,000 A primary) and a definite-time delay of 0.25 seconds. While this would ride through current inrush, it did not provide any ground fault protection unless at least three transformers were in service. Therefore, this method was inadequate on its own.

An inverse-time overcurrent (51N) element was applied along with the definite-time overcurrent (50ND) element. It was set with a pickup of 2 A (400 A primary) and a very inverse-time characteristic with a time dial of 1. This is more sensitive than the 50ND element but takes 0.6 seconds to trip with 1,200 A of ground fault current applied.

The microprocessor-based MFR provided two distinct advantages for Nucor Steel to improve upon the protection described in Figure 3. First, it has multiple overcurrent elements, and second, it has voltage elements available. Nucor Steel engineers took advantage of this, knowing that, for a bolted single-line-to-ground fault, the voltage on the faulted phase reaches zero and on the other two phases reaches 1.73 per unit (pu). This can be seen in Figure 8, which shows the relationships of the prefault voltages (V_{apf}, V_{bpf}, and V_{cpf}) to the fault voltages (V_{bf} and V_{cf}) for a bolted single-line-to-ground fault on Phase A. It is also proven using symmetrical components in the appendix of this paper.

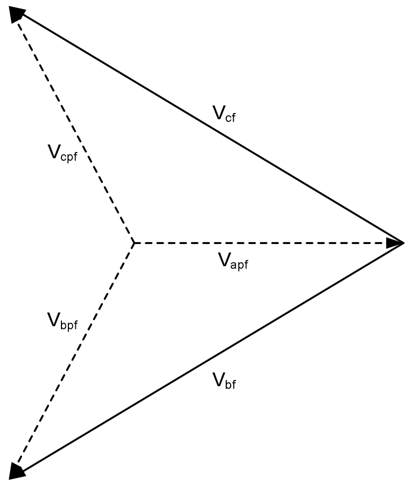

Figure 8. Prefault and fault voltages for a bolted single-line-to-ground fault on Phase A

Based on this knowledge, the Nucor Steel engineers set another level of instantaneous overcurrent protection (50N) with a pickup of 2 A (400 A primary) and no intentional time delay. They also set a phase overvoltage (59) element to pick up at 1.2 • $V_{nominal}$. This was used to enable (or torque-control) the 50N element whenever an overvoltage greater than 1.2 pu was seen on any phase. This approach allowed an acceptably sensitive instantaneous setting without requiring a time delay.

The resulting one-line diagram and tripping logic for the microprocessor-based MFR are shown in Figure 9. The MFR provides both instantaneous (50) and inverse-time (51) phase overcurrent protection from the 3000/5 phase CTs. The CT inputs are then tied together to make up a neutral, or residual, connection and run through a 5/15 auxiliary CT to the neutral CT input of the MFR. The MFR then provides instantaneous (50N), definite-time (50ND), and time-delayed (51N) ground overcurrent protection based on its neutral current input. The 50N element is supervised by an overvoltage relay (59).

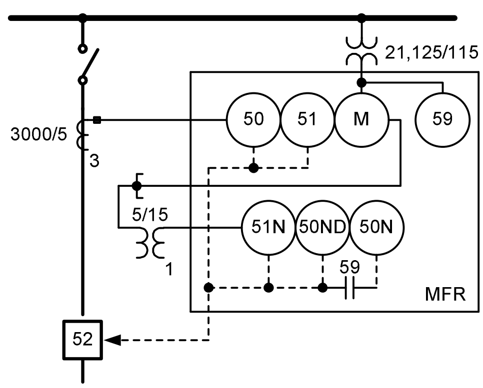

Figure 9. Revised MFR design

SENSITIVITY OF THE VOLTAGE-CONTROLLED INSTANTANEOUS OVERCURRENT ELEMENT

As part of developing this paper, the authors revisited the sensitivity of the voltage-controlled instantaneous overcurrent element to ensure that there would indeed be sufficient voltage on the unfaulted phases to allow the voltage-controlled instantaneous overcurrent element (50N) to pick up at its setting as expected. This is because once fault resistance (R_f) is introduced for a single-line-to-ground fault, the voltage on the faulted phase reaches something greater than zero and on the other two phases reaches something less than

1.73 pu. The sequence network diagram for a single-line-to-ground fault is shown in Figure 10.[5] It is assumed that the Santee Cooper system represents an infinite bus with respect to the Nucor Steel Berkeley power distribution system. It is also assumed that, for the transformer impedance, $Z_t = Z_{t1} = Z_{t2} \approx Z_{t0}$.

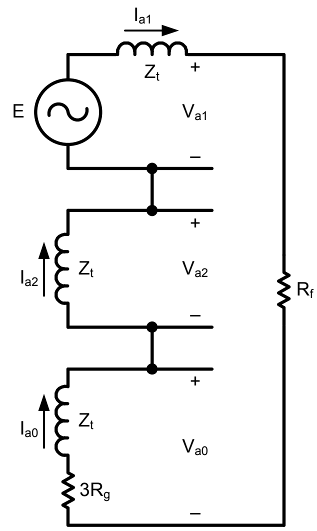

Figure 10. Sequence diagram for a single-line-to-ground fault

We can use the sequence network diagram shown in Figure 10, along with the method of symmetrical components, to calculate what the phase voltages will be for a fault at the minimum pickup of 2 A for the 50N element. We can then ensure the voltage-controlled 50N element will correctly trip the breaker at its minimum pickup, provided the unfaulted phase voltages are calculated to be above the pickup of 1.2 pu for the voltage element (59).

First, we calculate the base current and impedance based on the transformer ratings of 80 MVA and 34.5 kV.

$$I_{base} = \frac{kVA}{\sqrt{3}\ kV} = \frac{80,000}{\sqrt{3}\ 34.5} = 1,339\ A \tag{1}$$

$$Z_{base} = \frac{kV^2}{MVA} = \frac{34.5^2}{80} = 14.9\ \Omega \tag{2}$$

Next, because three transformers are normally in service and parallel, the equivalent transformer impedance (Z_t) is one-third of the rated transformer impedance.

$$Z_t = \frac{j0.09\ \Omega}{3} = j0.03\ \Omega = j0.002\ pu \tag{3}$$

Similarly, the equivalent grounding resistance (R_g) is one-third of the rated grounding resistance.

$$R_g = \frac{50\ \Omega}{3} = 16.7\ \Omega = 1.12\ pu \tag{4}$$

Knowing the effective neutral CT ratio (CTRN), we calculate the primary current at the pickup of the 50N element (50N1P), which is 2 A secondary.

$$\begin{aligned} I_{primary} &= 50N1P \bullet CTRN \\ &= 2 \bullet 200 = 400\ A \\ &= 0.29\ pu \end{aligned} \tag{5}$$

The sequence currents are then as follows:[5]

$$\begin{aligned} I_{a0} = I_{a1} = I_{a2} &= I_{primary} / 3 = 0.097 \text{ pu} \\ &= \frac{E}{3Z_t + 3R_g + R_f} \end{aligned} \tag{6}$$

Note, however, that $R_f >> 3Z_t$ and $3R_g >> 3Z_t$, therefore:

$$I_{a1} \approx \frac{E}{3R_g + R_f} \tag{7}$$

and:

$$R_f = \frac{E}{I_{a1}} - 3R_g = \frac{1}{0.097} - 3(1.12) = 6.95 \text{ pu} \tag{8}$$

From Figure 10, and neglecting Z_t, we can calculate the individual sequence voltages.

$$V_{a1} = E = 1\angle 0° \text{ pu} \tag{9}$$

$$V_{a2} = 0 \tag{10}$$

$$\begin{aligned} V_{a0} &= -E\frac{3R_g}{3R_g + R_f} = \frac{-1\angle 0° \bullet 3(1.12)}{3(1.12) + 6.95} \\ &= 0.33\angle 180° \text{ pu} \end{aligned} \tag{11}$$

Knowing the individual sequence voltages, we can calculate the associated phase voltages using the *a* operator, where $a = 1\angle 120°$.[5]

$$\begin{aligned} V_a &= V_{a0} + V_{a1} + V_{a2} \\ &= 0.33\angle 180° + 1\angle 0° \\ &= 0.67\angle 0° \text{ pu} \end{aligned} \tag{12}$$

$$\begin{aligned} V_b &= V_{a0} + a^2 V_{a1} + aV_{a2} \\ &= 0.36\angle 180° + 1\angle 240° \\ &= 1.22\angle -135° \text{ pu} \end{aligned} \tag{13}$$

$$\begin{aligned} V_c &= V_{a0} + aV_{a1} + a^2 V_{a2} \\ &= 0.36\angle 180° + 1\angle 120° \\ &= 1.22\angle 135° \text{ pu} \end{aligned} \tag{14}$$

During the fault, the unfaulted phases will reach a voltage of 1.22 pu. We can see from this that the voltage element (59), which has a pickup of 1.2 pu, should pick up and enable the voltage-controlled instantaneous overcurrent element (50N) at, or at least very near, the pickup setting of 2 A (400 A primary). Note that the accuracy of the voltage element of the applied relay is ±2 percent. The PT introduces some error as well.

Note that similar calculations performed with two transformers in service (not included in this paper) show that the voltages on the unfaulted phases increase to 1.32 pu because of the increased ground resistance and the corresponding increase in V_{a0}. Therefore, it is important to note that relay sensitivity is improved as available fault current decreases due to transformers being removed from service.

SUMMARY

As described in this paper, providing fast and secure ground overcurrent protection for an arc furnace during inrush conditions can be a challenge. The arc furnaces at the Nucor Steel Berkeley mill experienced several unintended operations due to high ground currents seen sporadically during transformer current inrush. Nucor Steel engineers approached the problem by first using the oscillography available in the event reporting of the microprocessor-based MFRs to diagnose the trip and characterize the inrush. They then used the knowledge they gained and the flexibility of the same relay to apply three different forms of ground protection: a definite-time ground overcurrent element (50ND), an inverse-time ground overcurrent element (51N), and a voltage-controlled instantaneous ground overcurrent element (50N). The addition of the voltage-controlled instantaneous overcurrent element that Nucor Steel engineers devised allowed them to provide the sensitivity and speed they wanted in a relay protection scheme, along with the security that the process required. This scheme was applied on all arc furnaces, including the 10 MW units that had not yet experienced an unintended operation. There have been no unintended operations of the overcurrent relaying on inrush since the new scheme was implemented in December 2010. Now that the scheme has been in service for over a year, Nucor Steel engineers are considering lowering the pickup of the 51N and 50N elements to make them more sensitive, especially for the unusual scenario where only one transformer is in service.

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APPENDIX: CALCULATING PHASE VOLTAGES FOR A BOLTED SINGLE-LINE-TO-GROUND FAULT

Consider Figure 10. In the case of the bolted single-line-to-ground fault, $R_f = 0$ and $3R_g >> 3Z_t$. Therefore, by inspection:

$$V_{a1} = E = 1\angle 0° \text{ pu} \tag{15}$$

$$V_{a2} = 0 \text{ pu} \tag{16}$$

$$V_{a0} = -E = 1\angle 180° \text{ pu} \tag{17}$$

Knowing the individual sequence voltages, we can calculate the associated phase voltages using the *a* operator, where $a = 1\angle 120°$.[5]

$$\begin{aligned} V_a &= V_{a0} + V_{a1} + V_{a2} \\ &= 1\angle 180° + 1\angle 0° \\ &= 0 \text{ pu} \end{aligned} \tag{18}$$

$$\begin{aligned} V_b &= V_{a0} + a^2 V_{a1} + a V_{a2} \\ &= 1\angle 180° + 1\angle 240° \\ &= 1.73\angle -150° \text{ pu} \end{aligned} \tag{19}$$

$$\begin{aligned} V_c &= V_{a0} + a V_{a1} + a^2 V_{a2} \\ &= 1\angle 180° + 1\angle 120° \\ &= 1.73\angle 150° \text{ pu} \end{aligned} \tag{20}$$