Surge Protection for Ladle Melt Furnaces

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INTRODUCTION

Vacuum circuit breakers (VCBs) are commonly applied to the primary circuit to switch Ladle Melt Furnace (LMF) transformers in melt shop applications that support rolling mill operations. Because of the well documented phenomenon of switching transients induced on the line of the furnace transformer due to the opening and closing of the vacuum circuit breaker, most LMFs in this application also have surge protection applied at the transformer terminals. This paper contains an analysis of one such location with two identical LMFs, each fed by a VCB where the LMF transformer terminals were equipped with primary surge protection consisting of surge arresters and snubbers. Recently, high transient counts and increased levels of combustible gasses in oils samples raised concerns and led to a field investigation, measurements, electromagnetic transient program (EMTP) simulations, and evaluation of the surge protection of both LMFs. Power quality measurements identified the transients experienced by the surge arresters at the transformer terminals. EMTP simulations reproduced the transients, determined a worst case switching event, and proper surge protection for each LMF transformer.

EVALUATION OF LMF TRANSFORMER SURGE PROTECTION

This steel making facility operates two identical LMFs in support of an EAF and rolling mill operations, each fed by a VCB. The LMF transformer primary terminals were equipped with surge protection consisting of surge arresters and RC snubbers. After several years the tips of the resistors of the resistor/capacitor (RC) snubbers repeatedly overheated during normal furnace operations. As a result, the resistors were removed from the circuit and the LMF transformers have been operated without them. Recently, the arresters located at the transformer terminals experienced more transient counts than previously recorded and transformer oil samples showed increased levels of combustible gasses. Concern over these changes led to an investigation involving switching transient measurements, switching transient simulations and an evaluation of the surge protection of both LMFs. This paper documents this investigation, provides an evaluation of the surge protection of the furnaces, and recommends several improvements to the surge protection of the furnaces.

System and LMF Circuit Components of Interest

This steel mill is served by a utility dedicated 34.5 kV substation located within 1 mile. The utility substation supplies the rolling mill circuits through separate 1,200 A SF6 breakers than those that feed both LMFs and the EAF. A static var compensator (SVC) rated 106 MVAR is located in the substation to provide voltage support and power factor correction for the EAF and both LMFs. A zig-zag grounding transformer is connected to the 34.5 kV utility bus to limit the ground fault current to 400 A. The utility breakers dedicated to the LMF transformers first feed 34.5 kV switchgear using 2 x 500 MCM EPR cables per phase as shown in Figure 1. These cables are 1,717 ft to LMF1 and 1,583 ft to LMF2. The 34.5 kV switchgear for each LMF circuit consists of a non-load breaking motor operated disconnect (MOD), a 1,200 A VCB, and a grounding switch. The VCBs feed 3/4 inch bus to the LMF transformers. The bus bars are 24 to 34 ft in length, depending on the phase. LMF1 and LMF2 have 16 MVA transformers with 4.98% impedance and 200 kV BIL primary winding.

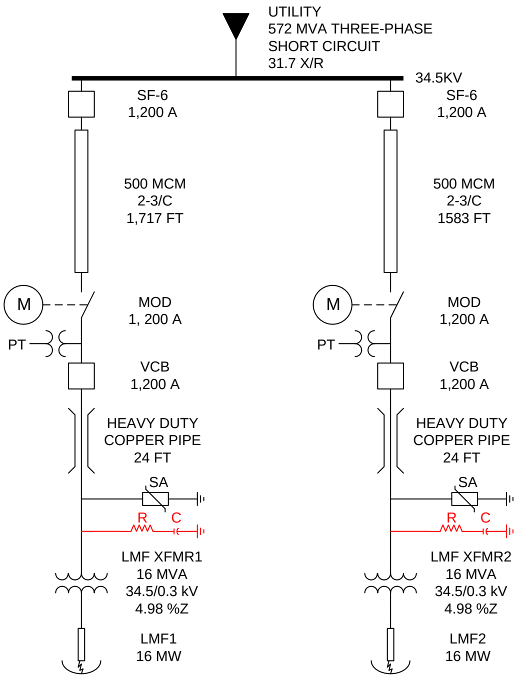

Figure 1. A diagram of the electrical distribution system for LMFs

LMF Surge Protection

The LMF transformer 34.5 kV surge protection consists of a surge arrester in parallel with a surge capacitor and resistor (removed) as shown in Figure 2. The surge arresters are rated for 36 kV and connected from the bushing of the LMF transformers to the ground jumper. The two surge capacitors in series with values of 0.125 μF at 24 kV and 0.25 μF at 13.8 kV are also connected between transformer bushing and ground. The effective surge capacitance is 0.083 μF. The resistor was sized after the manufacture of the LMF transformer and no record of the original designed value of the resistor is available. The resistors were removed from the circuit after operations commenced due to overheating.

VCB

The VCBs are rated for 1,200 continuous amps and are designed to interrupt up to 31.5 kA of fault current. Per the manufacturer, after 25,000 operations, the drive mechanism and vacuum interrupter chambers should be replaced. The mechanical service life of the VCB is 75,000 operating cycles. Vacuum breakers, such as the VCBs installed here, are good at extinguishing the arc of current flowing across their contacts. They perform so well that they are even able to quench an arc before a current 0, which is called current chop[1]. For the analysis in this paper, the current chop is modeled at 6 A to give a worst case scenario. Reigniting events occur when the breaker opens causing a voltage escalation which reaches a peak faster than the dielectric withstand capability of the breaker. The resulting arc across the breaker contacts may persist until the breaker is able to quench the arc. Opening a breaker shortly after energizing a transformer causes large voltage escalations and high frequency ring waves to be presented due to the chopping of the large inductive inrush current. These do not occur often but may due to improper protective device setup, or operator error.

Switching Operations

For short outage, such as between heats, the VCB is opened. The operations are reversed for energizing the furnace transformer circuits. After a short outage, the VCB is closed which energizes the furnace transformer. Each heat lasts for about an hour. For longer outages, such as for replacing the electrodes, the transformer circuits are isolated by opening the VCB, then opening the upstream MOD, and applying a protective ground. After a long outage, the furnace transformer circuits are energized by removing the protective ground, closing the MOD, and then closing the VCB. At the time of the investigation, LMF1 had around 1,300 counts on the surge counters while LMF2 had around 100 counts.

Background

The circuit characteristics determine the severity of the switching transient overvoltage and damage to the primary windings of the transformer. Such a transient overvoltage consisting of high magnitude and high frequency depends on a combination of the short distance of bus between circuit breaker and transformer, BIL of the transformer, inductive load being switched (transformer) and the circuit breaker switching characteristics: chop or reignition[2]. In the case of the furnace circuit, the vacuum breaker induced switching transients can be amplified by the stray capacitance of the short bus between the breaker and transformer interacting with the breaker chopped current.

Figure 2. The surge arrester, capacitor and resistor removed for LMF1

TRANSIENT MEASUREMENTS

Switching transient measurements quantified the transient overvoltages at the LMF transformer primary produced by switching of the VCB. The meters were setup to record on both transformers for four days to capture a variety of VCB open and close operations during normal heats as well as some MOD operations. Using this technique, the transient overvoltages at both furnaces could be compared, noting similarities and differences. A pair Power Quality Meters (PQMs), TM1 and TM2, were installed using voltage dividers placed near the terminals of each LMF. TM1 and TM2 were configured to capture high-speed switching transients at the primary-side of the transformer due to the VCB operation and then utilize the voltage dividers with a high-frequency response. A second set of PQMs (PM1 and PM2) were configured to trend basic power parameters as well as harmonics and capture voltage disturbances such as transients, sags and swells. PM1 and PM2 were installed at the metering current transformers (CTs) and potential transformers (PTs) on the line side of the VCB.

Equipment Setup

The test measurement setup consisted of voltage dividers and a transient recorder as shown in Figure 3. Proper measurement equipment was selected to assure accurate capture of the switching transient overvoltages at the 34.5 kV primary of the LMFs. The voltage dividers were sized for the system kilovolts and specified with a secondary output impedance to match the input impedance of transient recorder. The voltage dividers were placed on top of the transformer, as close to the LMF transformer bushing as possible, to detect any voltage reflections that occur when the incoming wave hits the sudden change in surge impedance of the transformer bushing. Vibrations were minimized by fastening the voltage dividers to a sheet of plywood clamped to the transformer. The voltage dividers were connected to the transformer primary bushing with a sweeping arc of number 10 insulated wire (120 V) as shown in Figure 3a. Care was taken to maintain proper phase-to-ground clearances between the voltage dividers and jumper wire to nearby equipment, as well as phase-to-phase clearances between the dividers. Figure 3b shows the measurement setup for LMF1 typical of both transformers.

Figure 3. (a) The voltage dividers installed at LMF1 primary, (b) The transient recorder and grounding for LMF1

Transient Trend

Many switching transient overvoltage events captured during the monitoring period are summarized in Figure 4. Figure 4 gives a chronological summary of the transient magnitude vs. time for the four-day monitoring period. This view shows a well-defined boundary with some higher peaks. The transient overvoltages peaked as high as 42.5 kV at LMF1 and 46.5 kV at LMF2. The higher magnitude transients occur during closing of the VCB. Figure 5a is representative of the higher magnitude transients at LMF1. Figure 5b is representative of those at LMF2. Both are similar in magnitude and do not exceed the BIL of the primary winding. LMF1 and LMF2 experienced a similar number of transients.

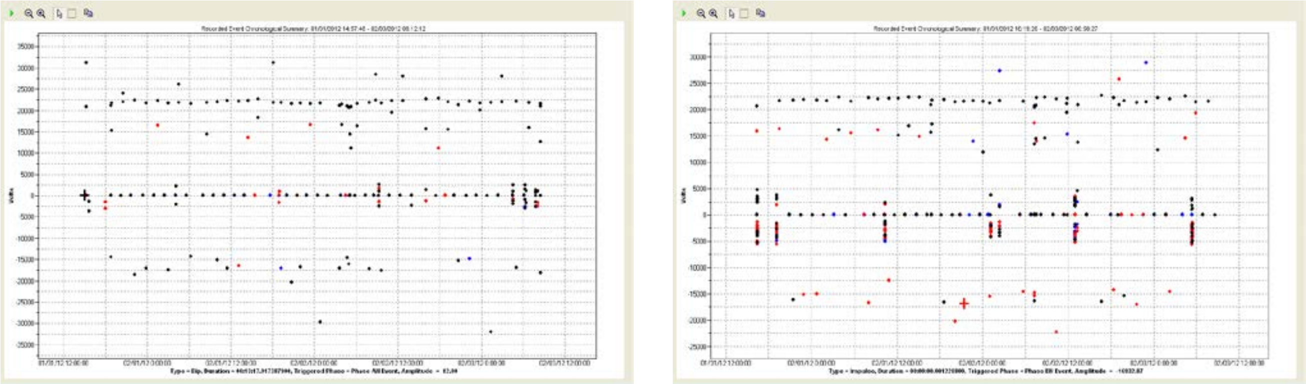

Figure 4. (a) TM1 showing captured transient overvoltage events at LMF1, (b) TM2 showing captured transient overvoltage events at LMF2

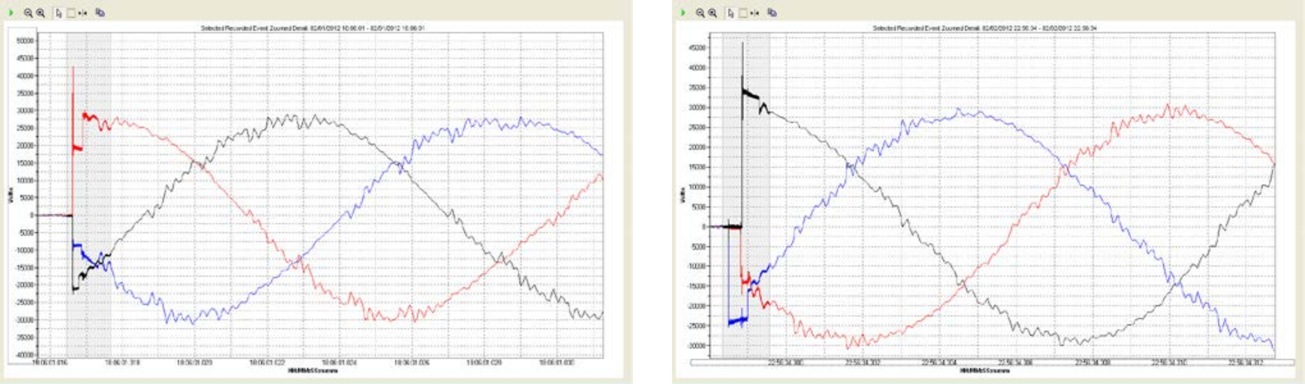

Figure 5. One cycle of voltage of the switching transient overvoltage (a) TM1 during Event 100, (b) TM2 during Event 339

Operating Sequence

Figure 6a shows the RMS voltage trend at the LMF2 transformer, as captured by the TM2 on 2 December 2012, and included 5 closings and 5 openings of the VCB in 4.5 min, totaling 17 recorded events. The transient overvoltages corresponding to these open and close operations in such a short period of time are of concern for several reasons, outlined below.

This type of repeated operation leads to a breakdown of the dielectric between the VCB contacts, resulting in prestrike of the arc as the contacts were closing. This type of high-frequency voltage will degrade the transformer turn-to-turn insulation over time. Prestrike actually occurs on the 3rd and 5th closing. The prestrike for the 5th closing is shown in Figure 6b. In both the 3rd and 5th closings, the breaker is closing in on a measurable amount of trapped charge, as shown in Figure 6a. The charge is trapped on the surge capacitors located at the terminals of the LMF. The initial charge is one per unit which decays due to the discharge resistor across the terminals of the surge capacitor. Per IEEE Standard 18, the caps must have discharge resistors and bleed-off the charge to 50V in 5min. In these two instances, not enough time has passed for the resistor to discharge the voltage entirely.

In comparison, a typical closing event is shown in Figure 5b above. The Temporary Overvoltage (TOV) is minimal and the voltage goes sinusoidal almost immediately after the VCB is closed. In contrast, the fifth closing in Figure 6b shows a breakdown of the dielectric between the VCB contacts lead to a pre-strike of the arc as the contacts were closing. This type of high-frequency repetitive voltage transient will degrade the transformer turn-to-turn insulation over time. There is a similar waveform for the third closing of the sequence.

Closing the MOD

After a long outage, the furnace transformer circuit is energized by closing the MOD and then closing the VCB. Transients of 100 kV at the PT for LMF1 as shown in Figure 7 persist for approximately 3 s every time the MOD is closed and are visible through the arcing as the blades approach. PT ferroresonance is one possible cause of these high overvoltages. Ferroresoance is a phenomenon usually characterized by overvoltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through a capacitance in series with the inductor[3,4,5,6]. Fortunately, the erratic voltage is damped within 3 s. This affect occurs at the MOD for both LMF1 and LMF2. The high peak due to the PT circuitry was not seen by the voltage dividers at the LMF transformer primary.

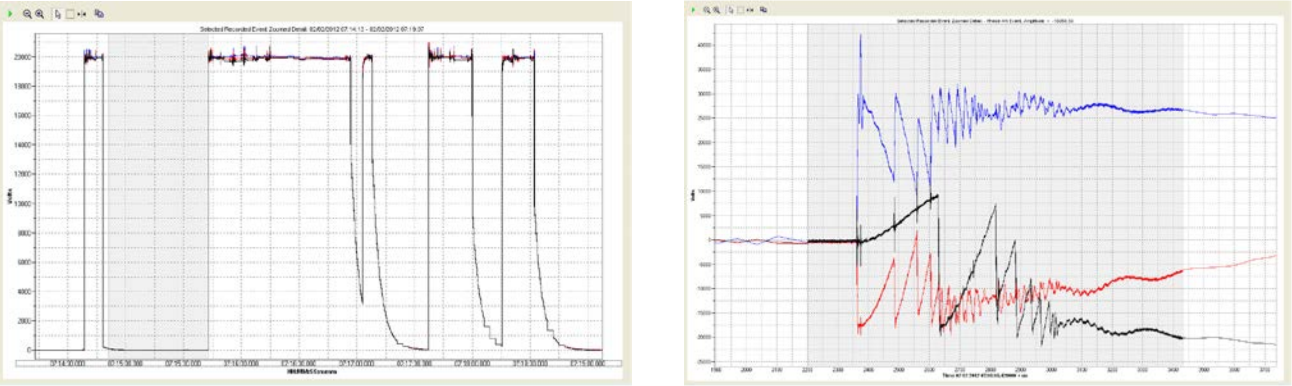

Figure 6. (a) TM2 during Event 221 showing RMS voltage for five open/close of VCB, (b) TM2 during Event 239 showing the fifth close of VCB results in pre-strike

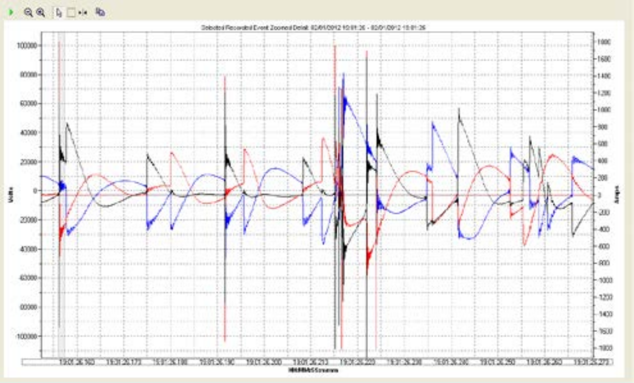

Figure 7. PM1 during Event 98 showing possible PT ferroresonance

EMTP ANALYSIS

The switching transient analysis was conducted using the Alternative Transients Program (ATP) of the EMTP. A detailed model of the significant elements in the furnace circuits was developed on the computer, which allowed simulations of the VCB switching. The significant circuit equipment that dominate the response was modeled. It was important to accurately represent the vacuum breaker chopped current, stray capacitance of the short bus, and inductance of the transformer being switched in the transient model[2]. The LMF transformers were modeled using the saturable transformer element in EMTP. Cables were modeled using distributed parameters elements or Pi equivalents depending on the time step. The breaker was modeled as an ideal switch with a chop current of 6 A.

Conditions which produced the worst-case transients during vacuum breaker switching were analyzed. The worst-case condition corresponds to the breaker chopping maximum current at the maximum point on the wave, based on the measured loads. The RC snubber components were sized according to the methods presented in the references[7,8]: 1) capacitor values were selected from standard surge capacitance values available at 34.5 kV, i.e. 0.125μF and 0.25μF and the resistor was sized to match the surge impedance of the incoming lines of 100 Ω. Other physical design considerations for the RC snubber were addressed per the reference[2]. The performance of the RC snubber was proven for this worst-case and therefore reduce the less severe transients produced during normal vacuum breaker switching.

Case Studies and Summary of Analysis

The following cases were run to determine the peak TOV experienced at the transformer terminals as well as the transient recovery voltage (TRV)[9] stress that is experienced by the breaker chopping current. The effectiveness of snubber design is evaluated for the conditions described in the cases listed in Table I. Opening the VCB with current chop with an unloaded furnace transformer is considered in Cases 1–4. The same opening conditions followed by re-ignition is considered in Case 5. Interruption of transformer inrush current is considered in Cases 6–10. The results of the transient switching analysis are summarized in Table I. For the three phases being switched, the largest magnitude of the TOV is labeled Vpeak and the highest frequency of the transient is given in kilohertz. The TOV at the transformer primary winding is compared to the transformer BIL of 200 kV and a ring frequency limit of 1,000 Hz. For the three phases being switched, the largest magnitude of the TRV is labeled Uc, the shortest time to crest of the recovery voltage is shown as t3, and the rate-of-rise of recovery voltage (RRRV) of those two values is given.

Table I. Case Descriptions with TOV Results and TRV Results

Case	Disturbance	Snubber Components			Transient Overvoltage		Transient Recovery Voltage		
		R (Ohm)	C1 (µF)	C2 (µF)	Vpeak (kV)	Frequency (Hz)	uc (kV)	t3 (µs)	RRRV (µs)
1	VCB Current Chop - 6A	-	-	-	142.0	**1.053**	**171.0**	220	0.777
2	VCB Current Chop - 6A	-	0.125	0.25	72.9	0.339	**82.5**	658	0.125
3	VCB Current Chop - 6A	100	0.125	0.25	70.6	0.336	**78.2**	480	0.163
4	VCB Current Chop - 6A	100	0.125	-	45.6	0.287	74.2	884	0.084
5	VCB Current Chop - Reignition	-	-	-	**290.7**	**3.378**	**268.0**	71	**3.775**
6	VCB Curernt Chop - Inrush	-	-	-	170.3	**4.630**	**296.0**	200	1.480
7	VCB Curernt Chop - Inrush	-	0.125	0.25	71.2	0.627	**76.9**	988	0.078
8	VCB Curernt Chop - Inrush	100	0.125	0.25	68.9	0.303	**80.2**	962	0.083
9	VCB Curernt Chop - Inrush	100	0.125	-	53.3	0.245	70.2	1494	0.047
Limits					200	1	74.5	24	3.1

Note: **Bold text** denotes value in excess of limits.

Breaker TRV is compared to IEEE/ANSI C37.06 limits for Uc, t3 and RRRV in Table I. Values determined by the simulation which exceed the limits are identified in the table in bold text. The existing snubber is able to drop the TRV magnitudes experienced to a similar value as the out of phase withstand ratings for a 34.5 kV circuit breaker per IEEE/ANSI C37.06 of 97 kV Uc and a t3 of 218 µS.

Case 1: VCB Current Chop

Figure 8a shows the results for Case 1 where the VCB de-energizes the LMF transformer under load. The TOV magnitude at the primary side of the LMF transformer was 142 kV, which is below the LMF transformer BIL of 200 kV. The frequency of 1.053 kHz, however, is above the recommended maximum of 1 kHz. Figure 8b shows the TRV across the VCB. The voltage peak of 171 kV is above the limit of 74.5 kV, and the voltage rise time of 328 µS is longer than the t3 time of 24 µS allowed by IEEE/ANSI C37.06.

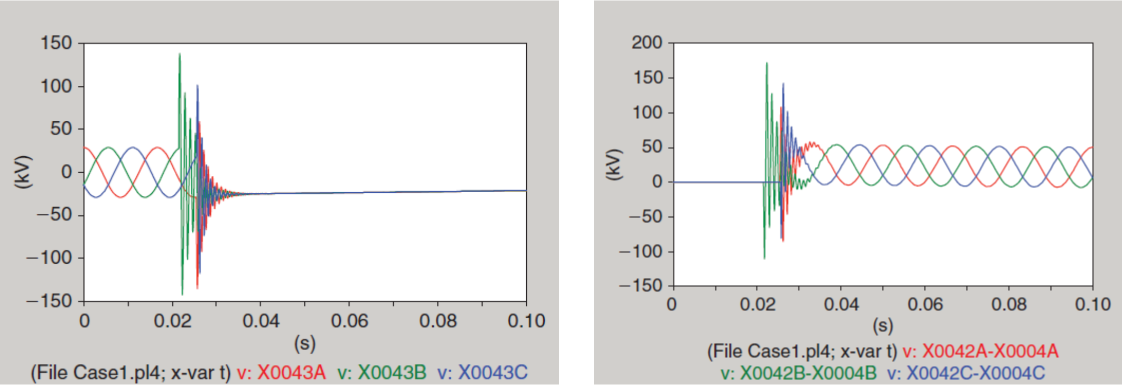

Figure 8. (a) Case 1, a transformer TOV with no snubber, (b) Case 1, a VCB TRV with no snubber

Case 2: VCB Current Chop – Surge Capacitor (Existing)

Figure 9a compares the results for Case 2 where the VCB de-energizes the LMF transformer under load with the existing surge capacitors at the transformer terminals. The TOV magnitude at the primary side of the LMF transformer was 72.9 kV, which is below the LMF transformer BIL of 200 kV. The frequency of 339 Hz is below the recommended maximum of 1 kHz. Figure 9b shows the TRV across the VCB. The voltage peak of 82.5 kV is above the limit of 74.5 kV, but the voltage rise time of 658 µS is longer than the t3 time of 24 µS allowed by IEEE/ANSI C37.06.

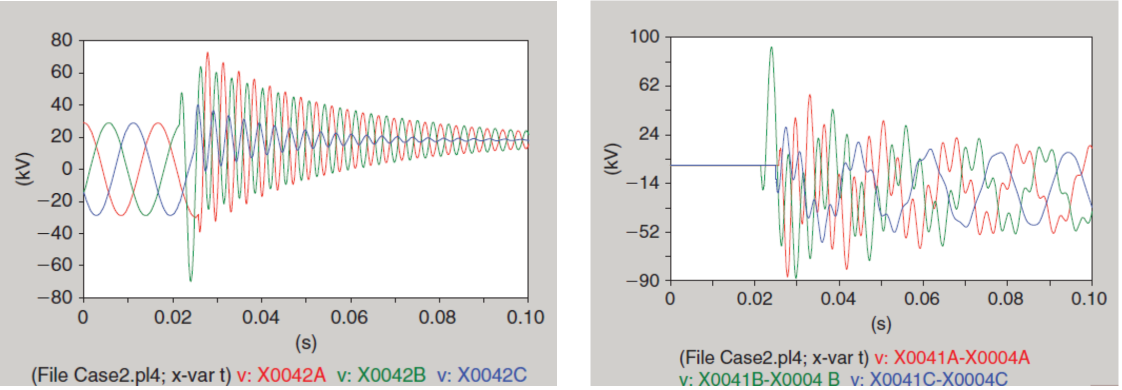

Figure 9. (a) Case 2, a transformer TOV with existing surge capacitor, (b) Case 2, a VCB TRV with existing surge capacitor

Case 3: VCB Current Chop – Snubber (Existing Capacitor, New Resistor)
Figure 10a shows the results for Case 3 where the VCB de-energizes the LMF transformer under load. The TOV magnitude at the primary side of the LMF transformer was 70.6 kV, which is below the transformer BIL of 200 kV. The frequency of 336 Hz is also well below the recommended maximum of 1 kHz. The resistor adds damping to the voltage ring wave at the transformer terminals. Figure 10b shows the TRV across the VCB Circuit breaker. The voltage peak of 78.2 kV is above the limit of 74.5 kV, but the voltage rise time of 480 µS is longer than the t3 time of 24 µS allowed by IEEE/ANSI C37.06.

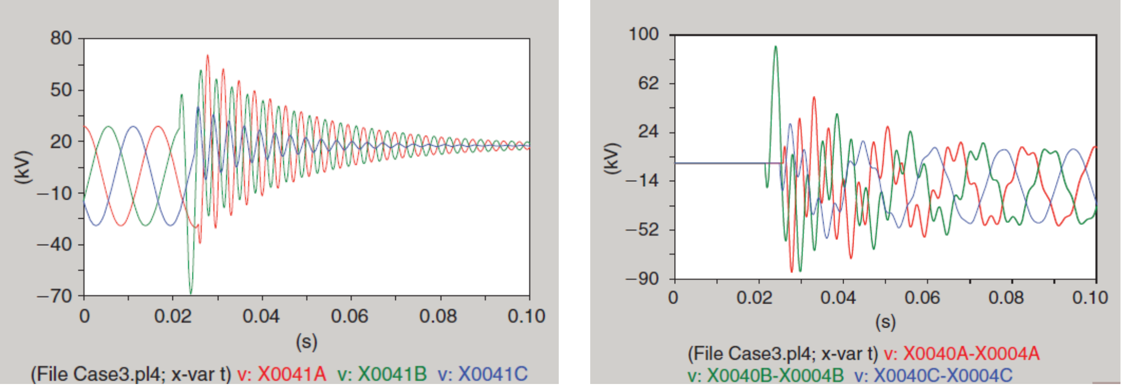

Figure 10. (a) Case 3, the transformer TOV existing surge capacitor and new resistor, (b) Case 3, the VCB TRV existing surge capacitor and new resistor

Case 4: VCB Current Chop – New Snubber (New Capacitor and Resistor)
Figure 11a shows the results for Case 4 where the VCB de-energizes the LMF transformer under load. The TOV magnitude at the primary side of the LMF transformer was 45.6 kV, which is below the transformer BIL of 200 kV. The frequency of 287 Hz is below the recommended maximum of 1 kHz. The new surge capacitor of 0.125 µF dampens the ringing that is present in Cases 2 and 3. Figure 11b shows the TRV across the VCB. The voltage peak of 74.2 kV is within the limit of 74.5 kV, and the voltage rise time of 884 µS is longer than the t3 time of 24 µS allowed by IEEE/ANSI C37.06.

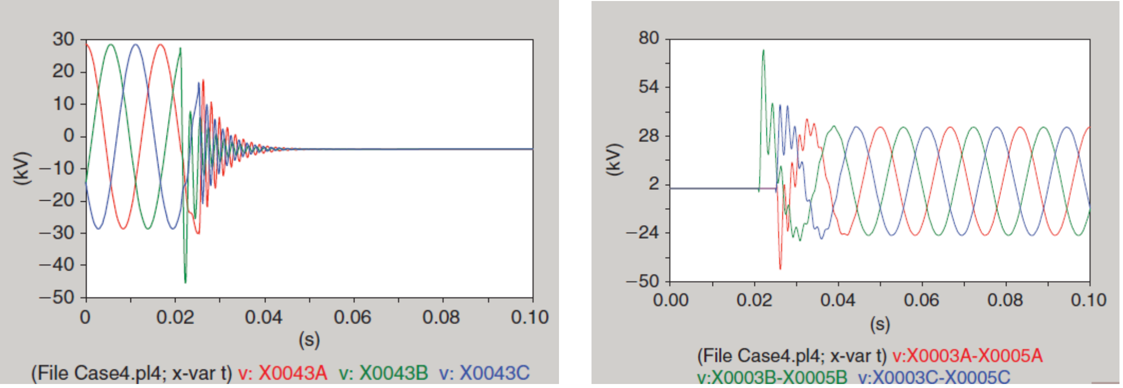

Figure 11. (a) Case 4, a transformer TOV new surge capacitor and new resistor, (b) Case 4, a VCB TRV new surge capacitor and new resistor

Case 5: Open VCB and Reignition – No Snubber

Due to the high-voltage magnitude across the VCB contacts, as shown in Table I, a restrike condition may occur. This was simulated in Case 5 and the results are plotted in Figure 12. Figure 12a shows the results for Case 5 where the VCB de-energizes the LMF transformer under load, which then causes a reignition event. The TOV magnitude at the primary side of the LMF transformer was 290.7 kV, which is over the LMF transformer BIL of 200 kV. The frequency of 3.378 kHz is above the recommended maximum of 1 kHz. Figure 12b shows the TRV across the VCB. The voltage peak of 268 kV is outside the limit of 74.5 kV and the voltage rise time of 71 μS is longer than the t3 time of 24 μS allowed by IEEE/ANSI C37.06. Reignitions cause the worst case TOV. Cases 6–9 were analyzed in a similar manner, and only the results are reported in Table I. The new snubber was effective in mitigating TOVs and TRVs for these cases.

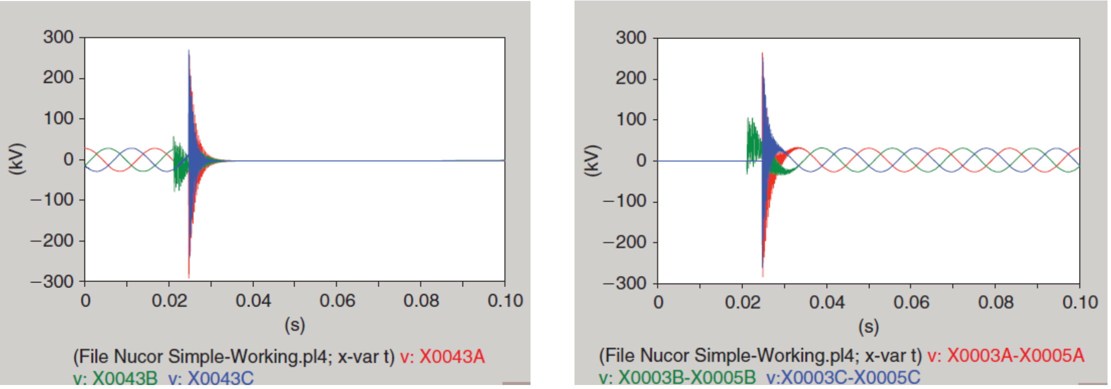

Figure 12. (a) Case 5, a transformer TOV with no snubber, (b) Case 5, a VCB TRV with no snubber

INSULATION COORDINATION

The insulation coordination evaluation was performed to determine if the existing surge arresters properly protect the LMF transformer primary windings from high transient overvoltage. The surge arrester discharge characteristics were compared with the transformer withstand ratings to ensure the protective margins of IEEE/ANSI C62.22 were met or exceeded. The surge arrestor was also evaluated on the basis of maximum continuous overvoltage (MCOV).

Selection of Surge Arrester MCOV

The 36 kV arrester with 29 kV MCOV used to protect the 34.5 kV primary side of the LMF1 and LMF2 transformers was checked. The standard operating voltage for a bus on a 34.5 kV system is 34.5 kV x 1.05 = 36.2 kV. For a resistance grounded system, the maximum line-to-ground voltage for a phase-to-ground fault is the full line-to-line voltage of 36.2 kV. The MCOV capability for the arrester must be at least 36.2 kV for line to ground faults that are expected to persist. For a resistance grounded system, if line-to-ground faults are expected to be removed, the temporary overvoltage capability of the surge arrester may be used in determining the proper ratings. The surge arrester in this application had a rating of 39.4 kV for faults expected to be removed within 10 s. In discussions with the utility engineer, line-to-ground faults on the utility system supplying the LMFs will be removed in under 0.3 s. Therefore, the arrester used to protect the primary windings of the LMFs has adequate capability for the expected temporary overvoltages.

Transformer Protective Margins

The protective margins are determined as below, and must equal or exceed IEEE/ANSI minimum protective margins[10]:

Protective margin = (Chopped Wave Withstand / Front of Wave – 1) x 100% (1)
with 20% minimum margin

Protective margin = (Basic Impulse Level / Maximum Discharge Voltage – 1) x 100% (2)
with 20% minimum margin

Protective margin = (Basic Switching Level / Switching Surge Sparkover – 1) x 100% (3)
with 15% minimum margin

Now calculate the protective margins with 14 ft of arrester lead wire length using (1)–(3):

Protective margin = (220 / 178.22 – 1) = 23%

Protective margin = (200 / 108.8 – 1) x 100% = 84%

Protective margin = (166 / 93.7 – 1) x 100% = 77%

SURGE PROTECTION EVALUATION AND IMPROVEMENTS

Evaluation of Measured Transients

No arrester counts or transients of a severe enough magnitude to cause an arrester operation were measured during the three-day monitoring period as shown in Table II. Excessive, rapid VCB operations are occurring on LMF2 which is evident by the 5 breaker operations that occurred between 7:14:27 a.m. and 7:18:15 a.m. on Feb 2, 2012 shown in Figure 6. This rapid reclosing of the VCB does not allow enough time for the dielectric medium surrounding the contacts to fully recover. Fortunately, the only ignition events that occurred were prestrike. If a reignition were to occur during the opening of the VCB, a much higher TOV/TRV would result on the furnace transformer and breaker. (see Case 5.) We suggest that at least 5 min should be allowed in between the breaker opening and reclosing for the dielectric to fully recover and the charge to bleed off the surge capacitor. This may be accomplished by placing a time delay in the closing of the breaker in the control system. At a minimum, the operator practice should be revised. We also suggest that a damping resistor be added to the secondary of the PT a proven solution[11,12,13], which can be easily implemented by using a switchgear heater. This added load will provide a method to dissipate the possible ferroresonant energy.

Table II. Surge Arrester Counters

Furnace Transformer	Phase A	Phase B	Phase C
LMF1	1215	1379	1325
LMF2	94	116	81

Switching Transient Evaluation

The existing surge capacitor and surge arresters at the terminals of the LMF transformers are not enough to properly protect the transformers from switching surges that occur due to the opening and closing of the VCB. The TOV at the LMF transformer and the TRV of the breaker exceeded the limits in Cases 1 and 5. Therefore, based on the results of the study, the we recommended installation of a new RC snubber network with ratings given in Table III, and installed at the terminals of the two LMF transformers as shown in Figure 13. This new RC snubber network should be created by removing the existing series surge capacitors rated 0.25 µF at 13.8 kV and 0.125 µF at 24 kV and should be replaced with a single capacitor rated 0.125 µF at 35 kV. Then, a single 100-Ω resistor should be installed on the line side of the new surge capacitor. This new RC snubber along with existing surge arrester will ensure no switching transients will damage the VCB or the transformer[2,7]. As is shown in Case 4 and 9, this new RC snubber is able to effectively dampen the transients seen at the transformer terminals as well as across the breaker contacts.

Table III. Recommended Snubber Resistor and Surge Capacitor Ratings

	Recommended Resistor				Recommended Surge Capacitor		
Solution	R (Ohm)	Peak Energy (kJ)	Power (W)	Vpeak (kV)	Vrms (kV)	C (µF)	Poles
New	100	17.5	1000	35	35	0.125	1

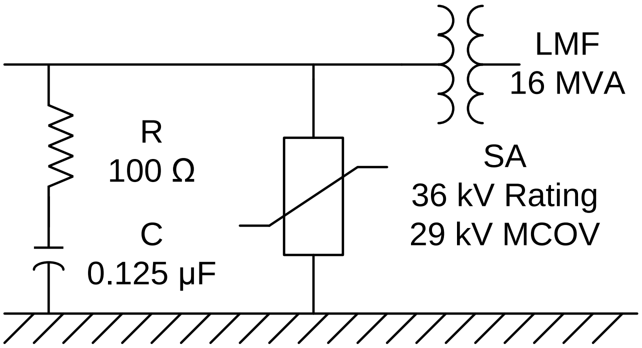

Figure 13. Snubber and surge arrester arrangement

The noninductive resistor shall have a value of 100 Ω and will be able to withstand a 35 kV peak, 17.5 kJ, and 1,000 W of continuous power. The resistor may be standalone or mounted on a glastic sheet for support. If the resistor is mounted on glastic, then the resistor clamps should be of the type with “turndowns” that do not come loose due to vibrations that occur during typical LMF operation.

Insulation Coordination

The existing surge arresters that protect the primary side of the LMF transformers are sized to take advantage of their temporary overvoltage capability. They are properly sized for a line-to-ground fault that will be removed within 10 s. The utility confirmed ground faults will be removed in under 0.3s.

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CONCLUSIONS

An investigation was conducted to address recent high transient counts and increased levels of combustible gasses in oil samples from both LMF transformers at this steel-making facility. Power quality measurements were taken to quantify the transients experienced by the surge arresters at the transformer terminals. Transient simulations were conducted to reproduce the transients and determine worst-case switching events. These simulations were used to properly size new surge protection for each LMF transformer. A new RC snubber consisting of components with robust ratings was recommended for installation with the existing surge arrester at the terminals of each LMF transformer.

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