Minnesota Power's Upgrade of Network Transformers

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On the evening of October 31, 2008, Transformer #1 at Minnesota Power's (MP's) YMCA Network Vault exploded violently and a huge fire ensued. This paper will provide a short description of network substations and will describe MP's restoration effort and actions to preclude a similar event in the future.

MINNESOTA POWER BACKGROUND

Minnesota Power is a division of ALLETE. MP serves approximately 144,000 customers in northern Minnesota. The bulk of the residential customers are in the Duluth/Cloquet area, with additional service areas in the communities around Little Falls and Eveleth, Minnesota. The Superior (Wisconsin) Water, Light and Power operation is also part of ALLETE. MP also serves 16 wholesale Municipal customers, five taconite operations, and several large paper mills. The load at the various taconite operations ranges between 30 and 200 MW. Over the summer of 2011, MP and the City of Nashwauk jointly signed agreements with Essar Steel to provide between 70 and 110 MW of capacity for a new taconite plant which is being built inside of the City corporate limit and electrical service territory. MP's main source of energy is still primarily coal fired conventional power plants. However, MP is also Minnesota's largest supplier of hydroelectric generation with over 100 MW installed hydroelectric capacity. MP has ten 2.6 MW Clipper wind turbines in operation on the US Steel Minntac property north and east of Mountain Iron and is in the process of commissioning almost 300 MW of wind turbine capacity in North Dakota. The output of the wind turbines will be shipped on a 465 mile 250 KV +/- DC line to the Duluth area. In addition, MP has signed an agreement to exchange wind capacity from North Dakota and hydroelectric capacity from Manitoba Hydro. The agreement will allow MP to "bank" wind produced energy against future hydroelectric generation.

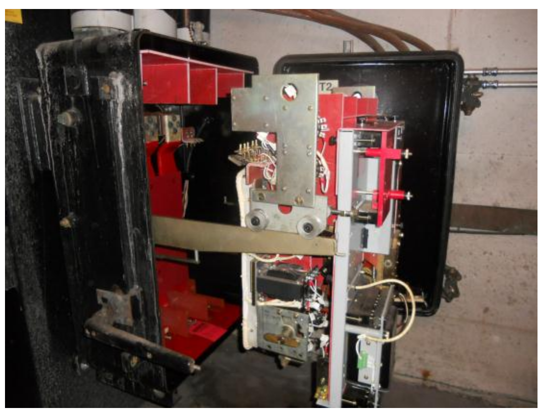
BRIEF DESCRIPTION OF NETWORK SYSTEMS

Network distribution systems are typically applied in urban areas having high load densities and limited space for conventional above ground substations. With the exception of Duluth's downtown, network distribution systems are not appropriate in other areas that MP serves. A typical network transformer vault might be 10 feet high, 10 feet wide, and 40 to 50 feet long, usually unnoticed under a section of sidewalk. The only indication of the presence of a network vault would be the ventilation openings, removable hatch covers, and access covers at the ends of the vault. Even though this might sound relatively large, by the time that the transformers, cables, and busbars are installed, vaults become congested at best. By definition, the term "network" implies multiple individual sources coupled into a common distribution system. In MP's system, its three network vaults are not interconnected at the secondary voltage level of 480Y/277 Volts. Instead, multiple transformers are installed in the same vault. (Some network systems are operated at 208Y/120 Volts.) The YMCA vault included three 1000 kVA 14,400 Volt Delta to 480Y/277 transformers of approximately 1970 vintage.

Transformers and other equipment installed in network vaults are unique in that they are essentially designed to operate under water, as well as in high temperatures and an environment that seems to attract dirt, leaves, and cigarette butts. Construction of Network Transformers is covered under ANSI C57.12.40. Conventional Network Transformers have a specialized oil filled primary switch and a throat mounted load rated secondary switch called a Network Protector. The primary switch typically has three positions: On, Off, and Ground. The switch is interlocked such that it cannot open if the secondary device (network protector) is closed and carrying current. This is necessary because the primary switch is not rated to interrupt load current. An unusual feature of the standard primary switch is that it can be switched to ground the incoming primary cable. The switch is interlocked so that it cannot transfer to the ground position if the secondary of the transformer is energized. Some utilities allow their personnel to ground the cable with this switch and work on the cables. MP's switching and grounding practices require a visible open, so the grounding feature is not really used to any advantage. In addition, having the ability to ground a feeder by operating a switch causes concern for the System Operators because of the possibility of being able to switch a ground into a feeder. Because of the difficult interlocking built into the primary switch, it is not possible to automate the switch. After the October 31 event, MP's personnel became increasingly hesitant to operate the primary switch to energize or de-energize vault transformers. Hence, efforts began to locate a primary switch which could be operated automatically.

Although network protectors have current sensing capabilities, overcurrent protection is not a function of the network protector. (Because of the extremely high fault current capacities in the network system, current limiting fuses are installed between the load bushings of the network protector and the buswork.) Controls in the network protector sense the relationship between voltage and current thru the network protector and switch additional transformer capacity into the network as appropriate. However, the critical function in the network protector is to sense reverse current flow into the transformer secondary and to isolate the transformer and its associated primary feeder from the network in cases of a feeder trip or fault on the feeder or transformer. Because of this feature, a network system with multiple primary feeders is an extremely reliable source of energy. In the past, network protectors were manufactured by GE and Westinghouse, but both companies have abandoned this product line. Two different companies have taken over parts support and remanufacturing of these devices. MP had nearly completed a long term project to rebuild its network protectors when the October 31 event took place. The rebuilds included update of the controls to a modern microprocessor based system.

The picture below on the left shows the network protector in place but with the isolating links removed. The picture on the right shows the network protector rolled out of its waterproof enclosure.



DESCRIPTION OF FRIDAY OCTOBER 31, 2008 EVENT

MP was extremely fortunate when this event took place, in that it took place in the evening of Halloween Day. Pedestrian traffic and vehicle traffic were minimal and no injuries were reported. However, the event did make the front page of the November 1 Duluth newspaper. One of the local TV stations was able to obtain a videotape from a security TV camera across the street and show it on their evening news. It was determined that the failure was caused by overheating of the primary switch compartment which then overheated the oil in the transformer. Because this was not a true line to line or line to ground fault, the feeder didn't trip out until the actual explosion and fire took place. We are uncertain whether the primary switch cover bulged and exploded first or whether overheated oil from the transformer began spouting from the pressure relief valve and burst into flame. Regardless, there was an intense explosion which blew open the heavy concrete hatch covers and destroyed the access ladder enclosure at the opposite end of the vault. In the ensuing fire, most of the primary and secondary cables inside the vault were destroyed. Even once the fire was put out, it was several hours before the transformer cooled enough to allow access to begin cleanup and repair. The other two transformers were not damaged by the fire. Although the YMCA did not have a standby generator and the pool overflowed without the backup, the two large communication facilities which are served at this location had backup generation so their outages were minimal. Once MP crews were able to access the vault, the burned off primary and secondary cables were spliced and the busbar sections over the burned out transformer were removed. The failed transformer was removed and hauled to the Herbert Service Center for evaluation. The remaining transformers were placed back into service on late Sunday, November 2.

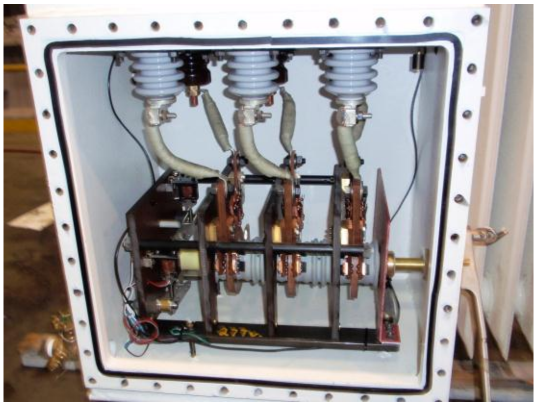
The picture below on the left shows the failed #1 transformer with burned out wiring and some of the hatch covers lying in the bottom of the vault. The picture on the right shows the collapsed walls for the ladderway at the opposite ends of the vault. The double layer of gypsum board was replaced with ¾" fire resistant plywood.

The pictures below show transformer #1 after it was removed to the shop and the opened primary switch compartment.

REBUILD OF TRANSFORMER #1

Although the remaining two transformers in the YMCA vault were adequate to carry the load on this network, it was decided to proceed with rebuilding the failed transformer on a priority basis because of the age of the remaining transformers and the fact that combustible gas analyses of these units were above normal. Jordan Transformer was selected for this work. The transformer would be rewound and the primary switch would be replaced with a Quality (brand) switch. Cooper FR3 non combustible fluid was chosen to eliminate future explosion risk. It is interesting to note that in spite of the fire and explosion, the original winding passed TTR and Megohm tests and could have been placed back into service. The repaired transformer was received in December, 2009, approximately a year after the fire. The rewound transformer was re-energized on November 1, 2010, including a new primary control switch to be discussed later. The transformer was placed in service after an overnight outage to connect the secondary conductors on November 17, 2010.

The pictures below show the rewound transformer as received and the new primary switch before it was closed and filled with oil at Jordan Transformer.



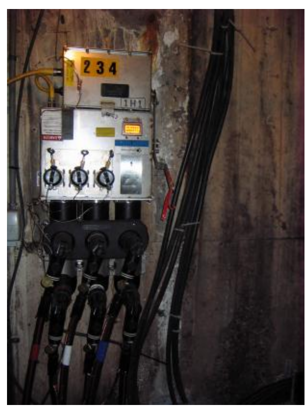
PROCUREMENT OF ADDITIONAL TRANSFORMERS
Because of the age and questionable condition of the remaining two 1000 kVA transformers in the YMCA vault and the three 1500 kVA transformers in Radisson vault, it was decided to proceed with ordering new transformers. Specifications were updated and a request for pricing was sent out to several vendors. CARTE of Winnipeg Manitoba was selected as the qualified low bidder. Purchase orders were issued in September and October 2009. Two MP engineers visited CARTE in early December 2009 to inspect the facility and the two transformers then in process. Although CARTE manufactures pole and padmount transformers, they appear to have a firm hold on a niche market of both network/subway and submersible transformers. The 1000 kVA transformers were received in January 2010 and the three 1500 kVA transformers were received in March. We were very satisfied with CARTE's willingness to work with us to adapt to the new switch described below. The new transformers were also ordered with Cooper FR3 fluid. The pictures below show the high bay section of the CARTE factory and the oil handling area.

DEVELOPMENT OF NEW PRIMARY SWITCH APPLICATION

As a fortunate coincidence, just as the network transformer specifications were being reviewed and updated, the Elastimold representative provided information on a compact vacuum interrupter switch that was designed for vault applications. It was available in single and three phase configurations and could be furnished with a motor operator and remote control capabilities, as well as overcurrent capabilities. Since MP did not require the grounding feature found in the normal network transformer primary switch, it was decided to eliminate the manual switch from the new transformers and have CARTE provide mounting studs for the Elastimold Molded Vacuum Interrupter (MVI) in place of the network primary switch. Standard URD wells and bushings were to be installed on the transformer. This would allow us to use standard elbows and URD cable to interconnect the MVI switch and transformer.

As noted above, the failed transformer was rewound and rebuilt to include the usual primary switch. In October, 2009, an order was placed for a single MVI switch for testing and evaluation. It was to be mounted on the wall in the YMCA vault adjacent to the rebuilt transformer #1. The first switch arrived in December. In January, we energized it with 120 VAC control power and were able to test operate the switch. However, we found that we didn't order the required computer interface cable to program the unit, so programming was delayed until the cable was received. Once we received the cable, we were successful in accessing and programming the overcurrent setpoints in March.

The picture below on the left shows the MVI switch as received. The center picture shows it installed on the wall of the network vault adjacent to Transformer #1. The picture on the right shows the motor control box for the switch. The yellow cable leaving the MVI on the top left connects to the control box.



We had hoped to reinstall the rebuilt #1 transformer with a new MVI switch before ordering the additional five units for the new transformers. However, this didn't happen as fast as hoped, so based on satisfactory evaluation of the first MVI switch in the shop, the five additional MVI switches were ordered in May 2010 in order to meet installation later in the year.

CONTROL AND INTERLOCKING SYSTEM

As noted earlier, the standard network transformer primary switch is interlocked so that it can not be opened unless the network protector is open and can not be moved to the grounding position unless the transformer is de-energized. Not having this switch, a different control strategy was developed:

- The network protector will open if the primary switch opens.
- High temperature sensing on transformer will open the primary switch.
- Remote control capabilities will be available for future SCADA installation.
- The existing operation counters will continue to be used.

The version of the MVI switch that was selected has an independent overcurrent sensing and trip system built onto the switch as well as a separate add-on motor operator. The motor operator is connected by a 30' cable to a small control box which has OPEN and CLOSE control switches. The 120 VAC to power the motor operator is fed to this box. The control boxes were mounted near the top of the access ladderway so that it is possible to reach down from the sidewalk level and operate the MVI. In addition, it is possible to plug a small remote control switch unit into a phone extension cord and operate the MVI an additional 25' away from the control box. The control box also accepts remote open and close contact signals and provides 5 Ampere circuit board mounted relay contact outputs to indicate open/close/trip status. Since we planned to feed the OPEN status as a closed contact to trip the network protector, we decided to install a standard 120 Volt AC relay to interface between the MVI control and network protector. Although all of the above is a relatively simple scheme, it still took considerable effort to draw up a layout for the relays and terminal strips and even more effort to check out and verify the operation. The circuits to consolidate the wiring for the network protector operations counters were also integrated into this system.

It was interesting to note that we tested the trip system before the network protector was connected to the 480 Volt bus. We closed the network protector manually and then opened the MVI. The MVI opened within 4 or 5 cycles. By the time that the 5 A relay contact in the control box closed and operated the relay that was to trip the network protector, the MVI had opened and there was no power left to unlatch the network protector. (Under real life situations, if the bus had remained energized from the other transformers, there would still have been power applied to the network protector which would have tripped it.)

INSTALLATION

Although it is not a simple task to remove concrete hatch covers and raise and lower transformers weighing 10,000 to 14,000 pounds thru an opening just big enough to squeeze the transformers thru, the substation Construction and Maintenance crew handled the project comfortably. The pictures below show the old Transformer #2 being lifted out and the new Transformer #2 being lowered into the vault. Note that the network protectors are attached.

The largest single problem that we encountered was the connection of the 480 Volt secondary conductors. We explored catalogs and checked on line but were not able to find a compact 480 volt rated switch capable of carrying 1200 to 1800 Amperes. The three phase busbars were spaced approximately 10" apart and were each composed of two or three ¼" by 4" copper bars. Even if cover-up were to be installed on the busbars, it was felt that it would be too hazardous to connect the 500 MCM copper jumpers onto the busbars while they were energized. In an effort to separate the individual phase conductors from each other, three sets of ¼" by 4" busbar, 8" long were designed to be installed below the existing busbars to provide staggered 4" by 4" "paddles" underneath the bus to attach the cables. In spite of this minor accommodation, it was necessary to plan a total power outage in the vault to connect the secondary conductors.

In the November outage, we planned to install the 4” by 8” paddles for #1 and #2 transformers, connect transformer #1, and disconnect transformer #3, all in time for the YMCA regulars to show up at 6 AM. We didn’t quite make this goal. The biggest single delay that we experienced was the long time it took to drill the holes in the busbars to attach the new “paddles”. Although copper is relatively soft, it does not drill easily unless you can maintain constant pressure to force the drill to cut. Without a drill press to do this, it was too easy to catch a piece of copper cutting under the bit and just turn around and around and not cut.

The pictures below show the busbar extensions for Transformer #2 and the completed connections on Transformer 1. Note that the current limiting fuses are enclosed in the PVC tube above the network protector.

As mentioned previously, the two largest customers on the vault had their own large diesel generators and had been able to continue operation thru the initial explosion and repair. As we began planning the outage to connect the rewound transformer #1, a problem was discovered with the fuel supply with one of the generators. As such, the first outage was delayed until the customer rented a large diesel generator which they installed temporarily to accommodate the November 2010 outage. However, to minimize disruption of computers in the normal work hours, all of the three outages were scheduled after midnight. MP provided a 25 kW diesel generator for the YMCA to maintain critical condensate and sump pumps during the outage. It should be noted that the personnel for the two larger customers were not intimately familiar with the power distribution and were not comfortable with MP asking them to open and lock out their main switch to prevent any backfeeds into the vault. One customer hired an electrician to be on site for the first outage to operate the switch and inspect the equipment and to be available in case the switch wouldn’t close properly. In the second and third outages, there was little reluctance because by that time, the customers had realized the importance of being familiar with their equipment and exercising the main breaker.

The remaining outages took place on December 16, 2010 and May 5, 2011. The final outage had been delayed until one customer could order and receive new main breaker parts which had been previously identified as defective. MP appreciates the patience and cooperation of our customers at the YMCA, QWest (Now Century Link) and AT&T in scheduling and coordinating the required outages.

EVALUATION AND RECOMMENDATIONS

We have been satisfied with the overall installation. The employees who are now able to push a button from above and outside of the vault to energize the transformer are still very pleased. We have not had any trips of the MVI switch. As with any project, there are details that remain unfinished, plans for future improvements, and items that we "wish we'd have done it a different way instead". These include:

- Replace #1 transformer instead of rewinding it;
- Documentation, documentation Never enough;
- Disconnect switch for 480 Volt conductors;
- Use of 600 Ampere T-body connectors on one end of the MVI to mount directly on corresponding bushings on the transformer;
- Rebuilding and upgrading ladder access hatch cover and railings;
- Installation of an arc flash detection system to open the primary switches; and
- Implementation of remote control via SCADA.

Although we had hoped to have the Radisson network vault completed by this time, it was discovered that asbestos fiber board had been installed around the two ladder wells. Plans were made to remove this material using qualified contractors, but other critical summertime construction projects have taken priority. We anticipate being able to restart this project over the winter. There will be a different set of problems for this installation in that the customer does not have a backup generator and they operate in a 24/7 customer environment. The customer's electrical room is in a lower basement level adjacent to the network vault. There are no spare openings which could be used to feed generator cables into the customer's equipment and there is no spare switch available to allow us to connect 4000 A of capacity into the switchgear. Disconnecting and reconnecting cables in the network vault to connect to a generator would take more time than it would take to disconnect and reconnect the 480 Volt cables to the transformers. It will take some extremely creative planning to coordinate this project.

MP's third network vault serves a building which had been a radio and TV station, but the station combined with another station, so the load on this vault is greatly decreased. Plans have been made to downsize this vault, possibly by installing a standard padmount transformer in place of the two remaining network transformers.