Protection Considerations for an Improperly Installed On-Load Tap Changer

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***Abstract*— On-Load tap changers (OLTCs) are critical transformer components when automatic voltage adjustment is required, such as in distributed generation systems. In June 2019, a defective OLTC was replaced with a brand new one, and shortly after re-energization, solar inverters started to randomly trip offline. This paper describes the investigation into these random nuisance trips, how proper commissioning could have prevented this issue, and what protection elements are suggested to detect this particular problem.**

I. Introduction

Large power transformers are widely used in the electrical grid, and one of their many applications includes the interconnection of solar farms to the utility. Due to voltage variations throughout the day, an on-load tap-changer (OLTC) is used to adjust the number of effective windings to match the utility's voltage. Proper functionality of the OLTC requires a specific sequence of operations and this component must be recommissioned if it is replaced. Improper replacement of an OLTC can cause severe transformer damage and traditional protection methods, such as differential protection (ANSI 87), might not detect this condition, therefore other protection techniques might be necessary. This paper analyzes the improper installation of an OLTC and suggests a protection method to detect this condition.

II. On-Load Tap Changer Theory

The purpose of a tap changer is to add or remove turns at the windings on either side of a power transformer to increase or decrease the voltage on the coupled side. A no-load tap-changer (NLTC) requires that the system be de-energized due to a temporary load loss during the tap change; an OLTC allows for a tap change to be performed with the system energized using a "make before break contact concept". For a general overview of oil-immersed OLTCs, refer to [1]. A live tap change is possible with the use of the following:

- Resistors and/or reactors that allow current transfer between the taps and limit circulating currents when in parallel,
- Bypass switches that allow isolation of the reactors,
- Selector switches that perform the actual tap change, and
- A vacuum interrupter that makes and breaks the current.

Because the making and breaking operation happens at the vacuum interrupter, the oil is not affected by the arc produced during the operation, and therefore contamination is prevented.

The OLTC described in this paper is a 32-step, 26.4 kV-rated tap changer, and its winding arrangement (simplified schematic) is shown in Figure 1 and [2]. Whenever a tap change is required, the OLTC works in the following manner:

- Switch P3 opens to allow current to flow through the vacuum interrupter.
- The vacuum interrupter opens and current stops flowing through the right-side reactor (P3-P4).
- As there is no current flowing, the selector switch (P4) moves to the adjacent tap.
- The vacuum interrupter closes and current flows again through the right-side reactor.
- The bypass switch P3 closes and the tap-changing operation is complete.

Note: A similar operation happens with the P1 and P2 switches to move the left-side reactor to an adjacent tap.

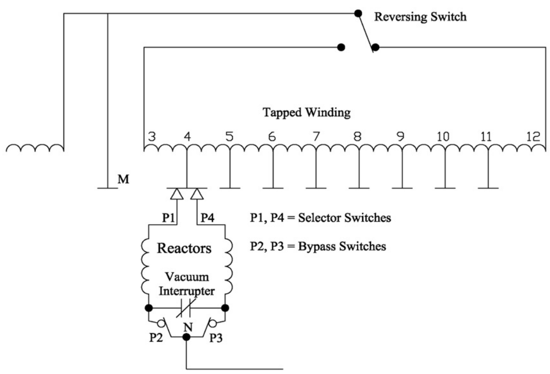

Fig. 1. On-Load Tap Changer Schematic (simplified)

III. Power System Description

The system discussed in this paper consists of a 40 MVA, 138 kV / 34.5 kV transformer, which is wye-grounded connected on both primary and secondary sides and a delta tertiary. It is connected to utility on the high-voltage side and to a 35 kV bus on the low-voltage side. Contrary to the norm, power flows from the low-voltage side to the high-voltage side via solar inverters connected to 2 feeders (F1 and F2) at the 35 kV bus. A capacitor bank is also connected to a third feeder at the bus (C).

The transformer is protected by primary and backup digital relays. The primary relay's differential zone of protection includes the transformer, the 35 kV bus, and the breakers connected to this bus, and it also senses voltage on both sides of the transformer. The secondary relay's differential zone of protection only includes the transformer, and the relay only senses voltage on the high-voltage side of the transformer. Because of the lack of signals, the backup relay has been omitted from this analysis. Figure 2 shows a simplified one-line diagram of the system (only the primary relay is shown).

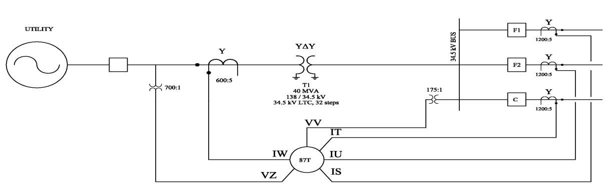

Fig. 2. One-line diagram, existing system (simplified)

IV. OLTC Installation and Upcoming Issues

Due to several leaks and damaged components, site personnel determined that the existing OLTC was defective and needed to be replaced. A new OLTC was installed during a maintenance outage, and the system was then re-energized. Shortly after energization, site personnel mentioned that solar inverters started to "trip offline randomly", and this would happen several times throughout the day. After a few days of continued unexpected outages, an investigation was initiated, and oil samples were obtained from the main transformer and from the OLTC. The transformer sample did not yield any major issues; however, the OLTC sample yielded an extremely high concentration of several gases, including Hydrogen (H2), Nitrogen (N2), and Acetylene (C2H2). According to Gill [3], the high concentration of these gases is indicative of high-energy arcing, with the key component being Acetylene. Due to the high-energy arcing condition, it was recommended to take the transformer out of service immediately and investigate the OLTC installation. Table 1 shows the gas concentration indicating problems at the OLTC (previous values are also shown for comparison).

TABLE I.
OLTC GAS CONCENTRATION

Sample Date	06/07/2019	04/29/2019
Top Oil Temp °C		22
Hydrogen (H2)	9000	0
Oxygen (O2)	8760	2070
Nitrogen (N2)	50100	13100
Methane (CH4)	2990	0.8
Carbon Monox. (CO)	69	15
Ethane (C2H6)	206	0
Carbon Dioxide (CO2)	297	248
Ethylene (C2H4)	6240	0
Acetylene (C2H2)	23800	0
Total Gas	101462	15434
COMB GAS	42305	16
EST TCG %	26.12	0.08
C2H4/ C2H2	0.26	0.00
Comb Gas Rate ppm/day	1,084.33	-1.30

V. Relay Event Data Collection and Analysis

As part of the investigation, relay event data was collected and analyzed. A negative-sequence overvoltage event trigger was enabled (V2 > 700 V) and several events were captured. Figure 3 shows the currents observed on 6/6/2019 @ 9:11 am on the high-voltage side (channel W) as well as the low-voltage side (channels T, U and V). At the moment that the event got triggered, B-phase current collapsed almost to 0, the angles of a- and c-phase currents drifted to almost 180 degrees (with a slight increase in magnitude), and B-phase voltage on the 19.9 kV (LN) side increased to 26.1 kV (31% increase). There was no change in voltage at the high-voltage side of the transformer.

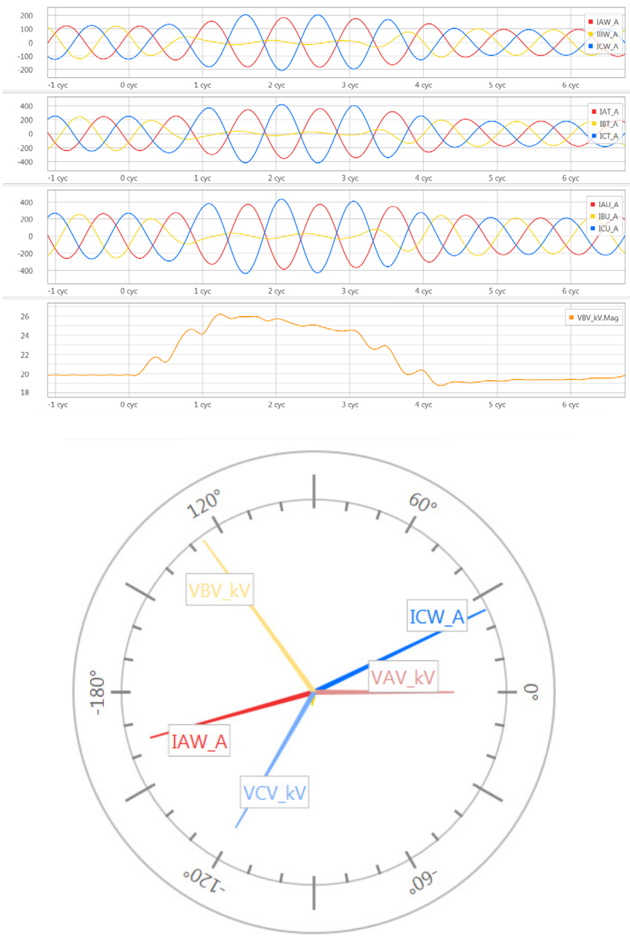

Fig. 3. Event on 6/6/2019 @ 9:11 am, phase currents and B-phase voltage (a) and phasor diagram (b)

The voltage and current symmetrical components also experienced changes during the event. Figure 4 shows the following:

- An increase of negative-sequence current (I2) in each set of currents (approximately 80% of nominal),
- An increase in zero- and negative-sequence voltage higher than 5%.

Because symmetrical components are present during traditional (short circuit) faults, these should not be used solely to detect OLTC problems; instead they can be used as an alarm to indicate that a problem is present in the system.

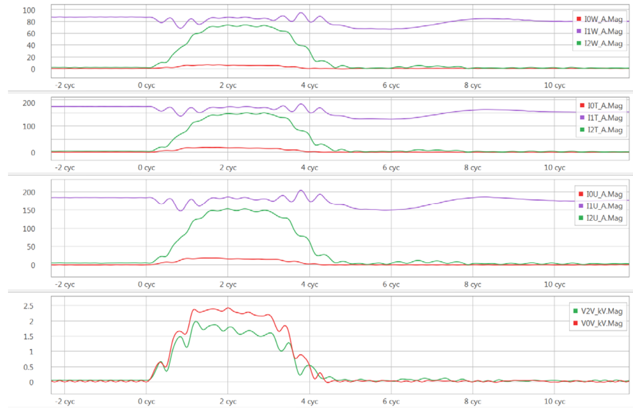

Fig. 4. Voltage and current symmetrical components on 6/6/2019 @ 9:11 am

Harmonic content was analyzed as well. The third harmonic (180 Hz) content registered during the event in Figures 3 and 4 exceeded 10% on B-phase voltage. Figure 5 shows the harmonic analysis in the COMTRADE event.

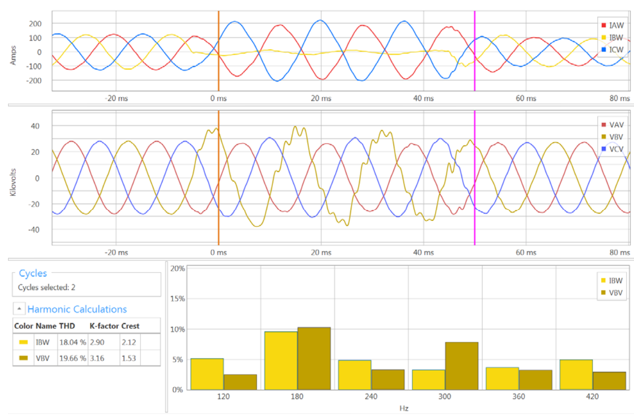

Fig. 5. Harmonic content for VB and IB, COMTRADE event

Table 2 summarizes the values collected on several events between 6/5/2019 and 6/7/2019: B-phase voltage, negative-sequence voltage, positive- and negative-sequence currents for channels W, T and U, and 3rd harmonic content. The three most extreme cases show that the phase overvoltage was higher than 30% nominal, the negative-sequence voltage was higher than 5%, the I2/I1 ratios are higher than 50% in each set of currents, and the 3rd harmonic content is higher than 5%.

TABLE II.
VOLTAGES AND CURRENTS OBSERVED USING RELAY EVENT DATA

Date	6/5/2019	6/5/2019	6/6/2019	6/6/2019	6/6/2019	6/7/2019	6/7/2019	6/7/2019
Time	9:40 PM	9:40 PM	9:11 AM	9:11 AM	9:08 PM	1:21 AM	3:34 AM	9:27 AM
VB RMS (kV)	21.8	21.9	26.1	25.8	21.95	22	21.47	26.5
%VNOM	109.5	110.1	131.2	129.6	110.3	110.6	107.9	133.2
V2 RMS (kV)	0.7	0.7	1.7	1.86	0.7	0.7	0.7	2.1
%VNOM	3.5	3.5	8.5	9.3	3.5	3.5	3.5	10.6
I2W (A)	0.87	0.89	73	55	0.73	0.9	1.3	60.4
I1W (A)	3.9	3.92	87	70	3.53	3.78	3.47	80.7
W - %I2/I1	22.3	22.7	83.9	78.6	20.7	23.8	37.5	74.8
I2T (A)	1.64	1.7	147	109	1.34	1.87	1.7	116.9
I1T (A)	8.11	8.65	172	138	8.32	8.13	8.65	162.8
T - %I2/I1	20.2	19.7	85.5	79	16.1	23	19.7	71.8
I2U (A)	1.89	1.6	153	116	1.84	2.1	1.76	123.79
I1U (A)	4.93	5.21	186	158	5.04	5.2	5.26	173.51
U - %I2/I1	38.3	30.7	82.3	73.4	36.5	40.4	33.5	71.3
3rd harmonic	2.37	2.19	11.28	6.07	3.75	3.95	2.85	10

Based on the above observations, a phase overvoltage element on the low-voltage side of the transformer will protect the transformer; an element set at 20% higher than nominal would have tripped the relay in 3 of the events, while setting it at 10% would have operated in 6 out of the 8 events. It is recommended to do the following:

- Enable an instantaneous phase overvoltage element trip at 20% higher than nominal, and a time-delayed overvoltage element trip at 10% higher than nominal (1 – 2 cycle delay).
- Enable an alarm when the ratio of I_2 to I_1 is greater than 50%
- Enable an alarm when V_2 is greater than 5%
- Enable an alarm when the 3rd harmonic content is greater than 5%.

The alarm triggers, as well as the 10% overvoltage delay, are dependent on the relay's capabilities due to the short duration of these "faults" and the fast processing interval required.

The new protection elements recommended were tested using the COMTRADE report from the event shown in Figures 3 and 4. Figure 6 shows the oscillography obtain by the newly generated event report, as well as both overvoltage elements (59P1 and 59P2) asserting at 20% and 10% respectively. The element set at 10% remained in the asserted condition for 49.95 ms.

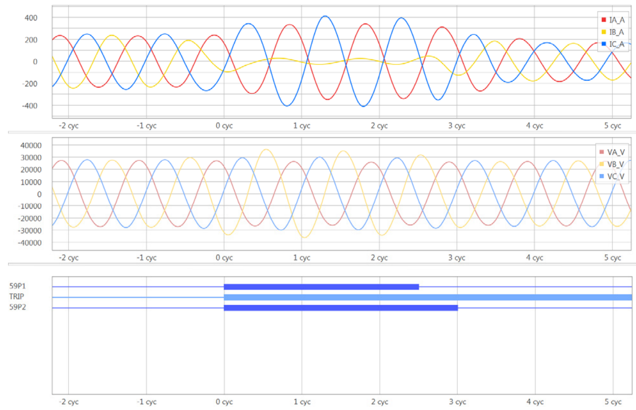

Fig. 6. COMTRADE event, overvoltage elements tested

VI. Field Observations

The oil sample results showed a problem in the OLTC, while the relay event data showed that the problem was related to B-phase. A procedure was provided by the OLTC manufacturer to perform a raise and a lower test to verify crossed leads and it is shown in detail in [4]. The procedure consists of the following:

Raise:

- Operate the OLTC in the raise direction from neutral to open P3 and P4
- Use a continuity tester to verify that P3 - P4 are a closed circuit
- Use a continuity tester to verify that P3-P2, P3-P1, P4-P2, & P4-P1 are an open circuit

Lower:

- Operate the OLTC in the lower direction from neutral to open P1 and P2
- Use a continuity tester to verify that P1 – P2 are a closed circuit
- Use a continuity tester to verify that P3-P2, P3-P1, P4-P2 & P4-P1 are an open circuit.

The above tests were passed on A- and C-phases; however, these tests failed on B-phase (there was no continuity between P3-P4 and P1-P2). During a visual inspection, severe damage was noticed at the selector and bypass switches due to arcing during load tap operations (see Figures 7a, 7b, and 7c).

Fig 7. Damage at the selector and bypass switches due to arcing

VII. Conclusion

An OLTC is an essential transformer component whenever voltage regulation is required while the transformer is energized. The installation of an OLTC requires a test to ensure that the leads for the selector and bypass switches have not been crossed; however, if such leads were accidentally crossed, overvoltage protection elements are recommended to send a trip signal to take the transformer out of service before further damage is created. Several alarms using symmetrical components and harmonic content are also recommended to advise site personnel of any abnormal conditions.

VIII. References

[1] Dohnal, D. *On-Load Tap-Changers for Power Transformers*, 2009. Available at *www.reinhausen.com/PortalData/1/Resources/tc/research_development/vacuum_technology/PB252_en_Power_Transformers.pdf.*

[2] Reinhausen Group. *On-Load Tap-Changer VacuTAP RMV-II Instruction Manual.* Available at *www.reinhausen.com/desktopdefault.aspx/tabid-310/94_read-65/.*

[3] Gill, Paul. *Electrical Power Equipment Maintenance and Testing*, Marcel Dekker, 1997. Available at *https://neta.netaworld.org/netassa/ecssashop.show_home_category.*

[4] Reinhausen Standards. *Testing for Crossed Preventative Autotransformer Connections.*

IX. Biographies

Alex Rangel is a protection and controls engineer for Saber Power Field Services, LLC. Alex is a NETA Level 4 certified, has been an IEEE member for 11 years, and has been a registered professional engineer in the state of Texas since 2014. He holds a BS in electrical engineering and an MS in engineering from The University of Texas at Austin.