

MEDIUM VOLTAGE REDUCED VOLTAGE AUTOTRANSFORMER STARTER FAILURES – EXPLAINING THE UNEXPLAINED –

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Abstract- For the past century the Autotransformer, or “Korndorfer” Starter has been a standard in the electrical industry. However for more than the past thirty years the autotransformer starter has been experiencing unexplained “High Voltage Stress” failures in typical applications. These failures have been reported on 2,400-volt starters from South America to 11,000-volt starters in the North Sea. In most cases the Zero Tap or the turns close to the zero tap are involved in the failure. This paper discusses the failure mode and the corrective action that prevents “High Voltage Stress” failures.

Index Terms – Korndorfer, Autotransformer, Failures, High Voltage Stress, Vacuum Interrupters

I. INTRODUCTION

The use of reduced voltage Autotransformer motor starters is a long-standing practice and is an economical method of reducing power system voltage dips during large motor starting.

In the late 1970’s, high voltage stress failure modes, in Autotransformer starters, began to be reported in the industry. Following are some of the failure reports that were published by a number of manufacturers and users:

- Multiple failures on a North Sea oil platform at 12 kV. The transformer neutral circuit, zero taps, kept failing. The solution was single-phase oil filled autotransformers. [1],[2].
- Four failures of the neutral tap-to-ground and tap-to-tap were reported on 20,000 hp 15 kV refiners in British Columbia. [3]
- In South America, transformer failures occurred on a 2400-volt motor starter when the air-brake contactors were replaced with vacuum.[4]
- A major electrical OEM reported system resonance that exceeded 100 kV.
- IEC 60470 recognizes the failure mode. Clause 6.102.7 requires the type test to be performed called “Change-over ability tests”. [5]
- In Southeast Asia layer-to-layer failures occurred when the starter was set on the 65% tap 6,600 volts 50 Hz.

II- OPERATING CONDITIONS WHEN FAILURES OCCURRED.

The author investigated failures on an offshore platform that experienced high voltage stress failures. An analysis of

the operating conditions at the time of failure indicated that the 4,160-volt transformers were connected on the 80% tap. The starter controls utilized time and not current as the basis of transition from reduced to full voltage.

One of the failures occurred when a bearing froze and the control circuit forced the starter into transition while at locked rotor current.

In another case the overload tripped the starter off line during a start attempt when the bearing locked up.

In an unrelated case, a defective current relay caused the starter to transition 0.5 seconds into the start cycle. This 4,160-volt starter was on an 80% tap.

A major office building had a 4,160-volt two-coil, three-legged autotransformer on the 65% tap fail after 8 years of operation. The replacement transformer failed some 4 months later, and its replacement failed in 3 weeks.

The failures ended when a current trap was installed to prevent transition before the motor starting current had dropped to 125% Full Load Amps (FLA). The trap operated many times until the chiller controller boards were changed out, and the trap has not operated since.

A 4,000 hp 4,160 volt starter, with a two-coil, three-legged autotransformer on the 80% tap, failed when the pump was blocked closed. The control was set to transition on time.

III. HIGH VOLTAGE STRESS FAILURE SYMPTOMS:

A. Zero Tap Circuit to Ground Voltage Strike

The zero tap circuit to ground failure, illustrated Fig 1, has occurred with voltages jumping in excess of 8.8 cm (3.5 in) through air. This circuit configuration has passed 75 kV BIL, and a 60 sec 30 kV power frequency dielectric test.

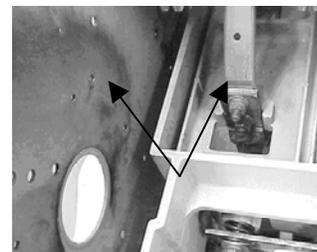


Fig 1. Zero tap Circuit to Ground

B. Tap-to-Tap Voltage Strike

This transformer, shown in Fig 2, failed from the 0% tap to the 50% tap underneath the tape. The distance was 3.1 cm (1.25 in). This configuration withstood a 60 sec 20kV power frequency dielectric test.

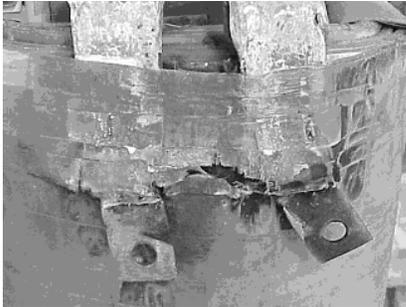


Fig. 2. Tap-to-Tap Strike

C. Layer-to-Layer Failure

This transformer failed layer-to-layer through two layers of .178 mm (.007 in) 410 Nomex. This configuration withstood a 60 sec 14 kV power frequency dielectric test.



Fig. 3. Layer-to-Layer Failure Point

Studies of these failures indicated a common thread: forced-transition on 4,160-volt autotransformers connected to the 80% tap.

IV. TEST PROGRAM 1991

For many years, manufacturers used two-coil, three-legged-core autotransformers.

After several failures, a test program was conducted on a 460-volt 150 hp motor to determine the voltages when two-coil, three-legged and three-coil, three legged transformers are transitioned both near locked rotor currents, at near full speed and at various taps. The test circuit is shown in Fig 5.

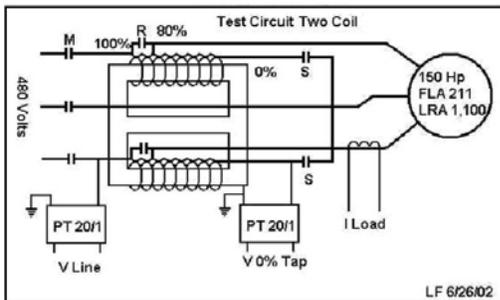


Fig 4. Two-coil, three-legged Autotransformer

Two-coil, three-legged: The test program found that during forced transitions and when connected to the 80% tap, the 0% taps voltage rose as high as 1,270% of the line-to-line voltage. These peaks appeared twice each cycle while the “S” and “R” contactor were open.

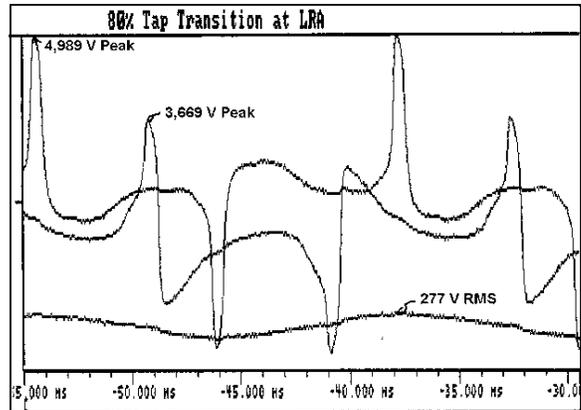


Fig. 5. Tap Voltages During Forced Transition

The voltages Fig 5 were recorded when the transformer was connected on the 80% tap with the transition taking place some 0.3 sec into a 4 sec acceleration cycle. The curves were recorded after the “S” contactor was opened and before the “R” contactor was closed.

When the motor was allowed to accelerate so the motor current decreased to 75% FLA, the voltage was only 2.6 pu voltage above normal.

When the same tests were run on the 65% tap, the voltage escalation was only 6.0 pu voltage rise above line-to-neutral voltage.

Three Coil Three Legged: The same tests were run with a three-coil, three-legged transformer Fig. 6. and the voltage on the zero taps was less than a 2.0 pu Fig. 7. at locked rotor.

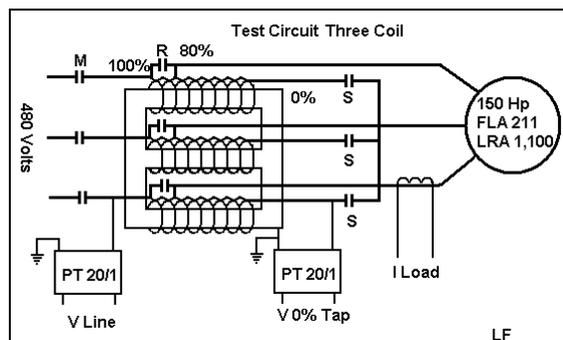


Fig. 6. Three coil Three Legged Autotransformer

Inferences: As a result of this test program, the two-coil design was no longer offered as standard. The control circuit was changed to require transition on current and trip on time-out if the current had not dropped below 125 % of FLA.

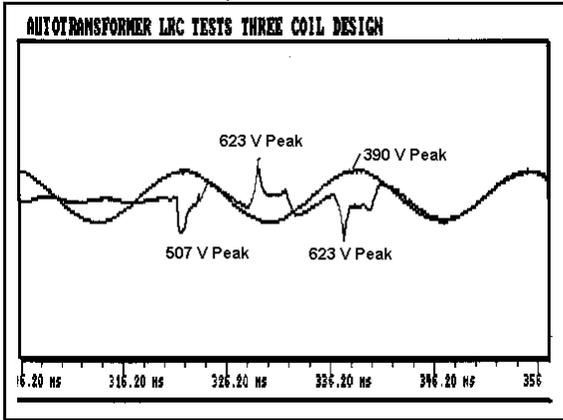


Fig.7. Tap Voltage Three Coil

V. TEST PROGRAM 2002

However, despite these changes high, voltage stress failures continued at the rate of two or three a year. The operating conditions of these failures were the same: 80% tap with a transition near locked rotor conditions on 4,160-volt systems. These failures typically occurred when the control circuit was set up to transition on time and a bearing failure occurred. Or, the load torque was higher than the motor torque causing the motor to fail to accelerate to full speed so it was forced to transition near locked rotor current.

A test program was established to identify the source of the failures. The first tests were conducted per IEC 60470 clause 6.102.7 without any indication of high voltages. The test loads were reactors and resistors to simulate locked rotor motor starting currents and power factor. The data acquisition system had a relative low frequency response of less than 250 kHz. The tests results confirmed the 1991 test data.

During the years 2001 and 2002, on an offshore platform, some 7 autotransformers failed, 5 of which were high voltage stress failures. The motors were 4,160 Volts 1,750 and 2,500 hp. All the transformers were on the 80% tap.

Good data of the operating conditions prior to and during the failures indicated the fault occurred during multiple starts near locked rotor conditions or during an over load trip.

A consulting engineering firm undertook a study of the power system and autotransformer circuit. The study did not identify voltages levels that the physical evidence indicated had to exist to create the faults.

The next set of tests was conducted in early December of 2002. The starter was an autotransformer rated for 378 to 491 LRA with tap at the 50, 65 and 80 % levels. These taps are compensated for a system voltage droop of 3% of locked rotor current during starting so the no-load voltages are 52, 68 and 83 % of line voltage respectively. The transformer has approximately 1% impedance at full load amps.

A TEFC WPII, 500 hp, 3,600 rpm, 4,160 volt, 62.5 FLA, 392 LRA, motor was tested with this autotransformer starter. The tests were conducted over 4 days in three different sessions with no evidence of high voltage being recorded. The scope's sample rate was set at 1 million samples per

second and the bandwidth set for 500 kHz. There was high frequency noise in the system that would trigger the scope if set any higher.

In January 2003 the tests were moved to an indoor lab. The power system (Fig. 8). for this lab is an ungrounded wye system, so a high impedance, low frequency ground was established using three transformers in wye, open-cornered delta and a surge capacitor of 0.5 μ Fd supplying the high frequency ground.

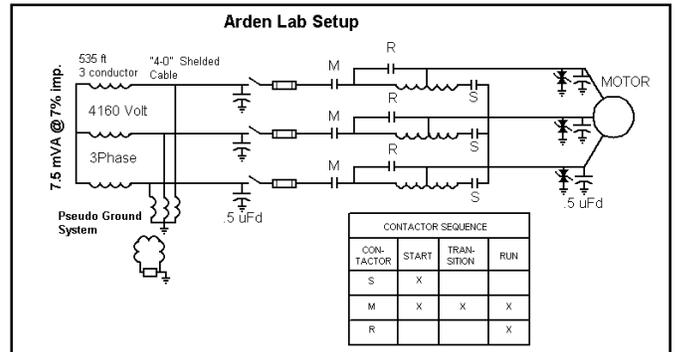


Fig. 8. Arden Test Lab Setup

Metering: The scope used was a 16-channel with 8 channels installed, with a sample rate of 10 mega-samples/sec per channel.

The high voltage measurement was made using a 40 kV x1000 probes for measuring the line, tap, and load voltages.

Currents were measured with clamp-on CT's. Their frequency response is +/-10% at 50 kHz.

Test Circuit: Voltage and current in the 0% tap circuit was measured and the line voltage on phase "A" as shown in Fig.9.

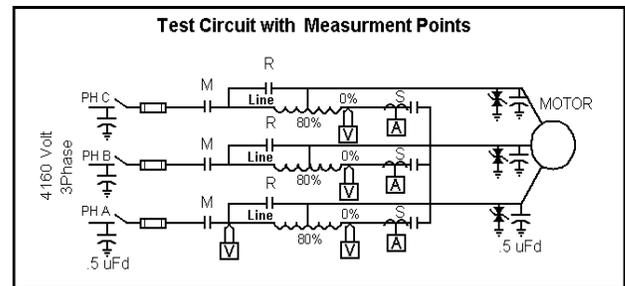


Fig. 9. Test Circuit Schematic.

The Scope was running at 10 million samples per second in each channel.

The motor acceleration time was 1.7 sec from stand still to 3,600 rpm.

Transition was set for 10 cycles 160 mSec into the motor start with "R" closing 10 cycles after "S" opened.

Test Results: After 5 more days of testing, the cause of the high voltage stress was observed with voltages exceeding 30,000 volts and fast transients of 30,000 to 70,000 volts/ μ Sec. The whole event was over in 500 μ Sec and

appeared at first to be noise. However one transient appeared during each test. When a current in one 0% tap reached zero, the VI (vacuum interrupter) would stop conducting and the voltage in that coil would escalate.

Case where the VI did not restrike: This test, shown in Fig.10, is where the current in phase "A" coil went to zero (at 200 μ Sec) when the VI extinguished the coil current. The VI did not restrike and the voltage across the coil escalated to 23,000 V and the voltage across the VI peaked at 25,000 V.

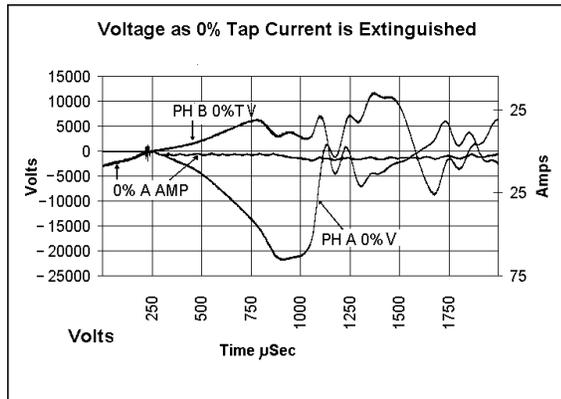


Fig. 10. Tap Voltage When Tap Current is Extinguished

The flux in phase "A" core leg was zero and the voltage develops as phase "A" core leg is saturating.

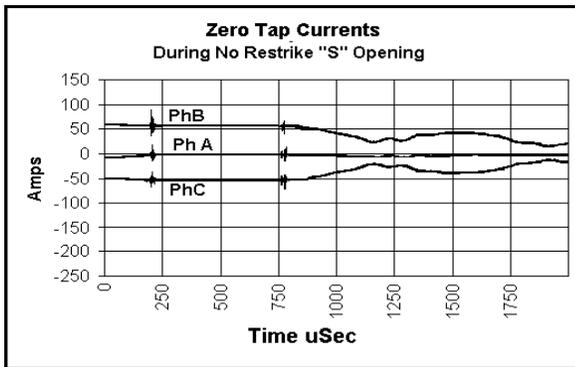


Fig.11. Tap Currents After One is Extinguished

The other two zero tap currents remained constant while the phase "A" core leg is saturating.

Case where the VI did restrike: This test, shown below, is where the current in phase "B" coil extinguished. The voltage across the VI went to 30,000 volts and arced across the open contacts. When the voltage across the coil collapsed, there were oscillations of unknown magnitude and frequency. This High dV/dT occurred six times until the core finally saturated.

David L Swindler [5], in his paper on Switching Resonance, estimates that, at this high dV/dT, inter-layer voltage escalation occurs in the order of 5 and 50 times normal layer-to-layer voltages.

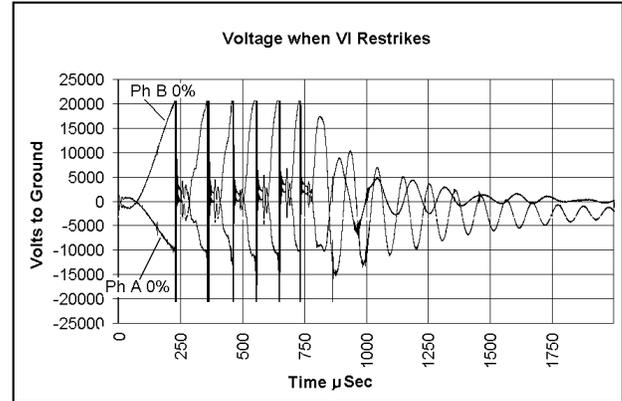


Fig.12. Voltage Across VI's When a VI Restrikes

Detailed look at a Restrike Event: When the VI struck (Fig. 13), the voltage change across the coil occurred in 0.3 μ Sec or less. This is a 50-70 kV per μ Sec event. The resonant frequency was estimated to be between 2 and 3 MHz.

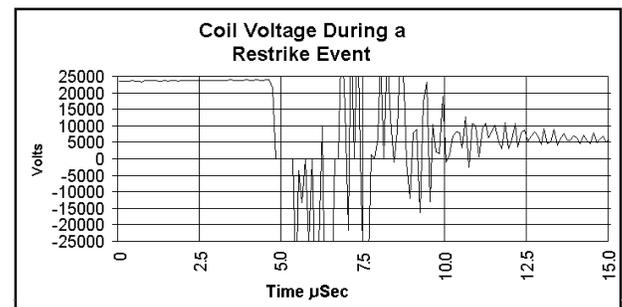


Fig. 13. Coil Voltage During A Restrike Event.

Case where transition was made below 125% of FLA: Other tests were run on all starting from near locked rotor to full speed, 50, 65 and 80% taps. Some starts were made with the "S" contactor open. Ten starts were made with each setting. The voltage escalation was observed on the 80% tap up to where the current began to fall off at 80-85% speed. The magnitude decreases somewhat as the speed increases.

This escalation of voltage was much less on the 65% tap around 600% vs. 1,200%. The 50% tap showed about 350-400%.

Inferences: When autotransformer starters are forced to transition before they reach near full speed they generate high voltages on the 0% taps with respect to the line voltages. The 80% tap generates dangerously high voltages, the lowest being relatively benign on the 50% tap. When motor starting controllers are configured for transition on sensing current reduction to a point below 125% FLA, these voltages will not be experienced. When time is used as a basis of transitions from reduced to full voltage changes, external system conditions can cause starting times to extend beyond the expected, resulting in dangerously high voltages being generated, thus current detection is the safest approach to utilize.

However, there are situations, deep well pumps where bypass valves are not possible, where the motor cannot accelerate to full speed and the current does not drop below 125%.

Solution: When 6 kV distribution surge arresters were installed from the 0% tap to ground, the voltage (Fig.14). was clamped to 13kV without the resultant high dV/dT across the coil. These voltages were observed only once during each motor start.

The current flowing in the surge arrestors was measured at 12-18 amps for 800 microseconds, which is well within the rating of distribution arrestors.

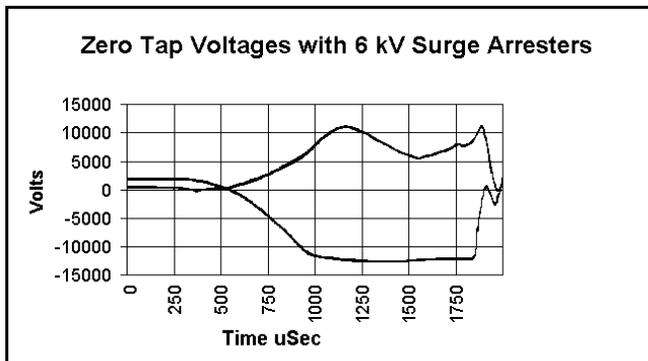


Fig.14. Tap Voltage With Surge Arresters

The surge arrestors are installed Fig.15. across the VI's and only two surge arrestors are required for two VI's. With a three pole three surge arrestors are required.

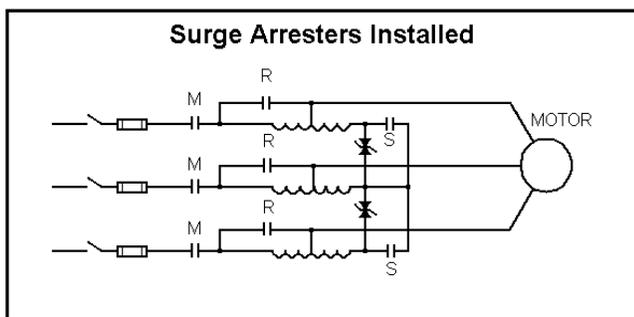


Fig.15. Surge Arresters Installed.

VI. Conclusion

The interaction of the vacuum interrupter and the magnetics of a 4,160V autotransformer when transitioned near locked rotor conditions and on the 80% tap develops very high voltages that result in flashovers 0% tap to other taps and 0% tap circuit to the autotransformer core or ground some where in the circuit. At other times, this high voltage causes the VI to restrike developing a very high rate of change in voltage. In this test series it was measured in the order of 50-70,000 volts per microsecond. This will result in layer-to-layer failure inside the transformer. The application of distribution metal oxide arrestors prevents the build up of dangerous voltage levels.

VII. REFERENCES:

- [1] SG Lawton *Problems Experienced with Korndorffer Autotransformers:*
- [2] SM Cargill, DG Edwards and SG Lawton: *Suppression of Voltage Transients Generated by Autotransformer Switching:*
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VI. Vita



Lawrence B. Farr was born in Port Arthur TX, December 17, 1941. He received his BSEE from Lamar State Collage of Technology, Beaumont, TX, and the MBA degree from the University of Detroit, Detroit, MI in 1978.

He was with the Air Force in Control Center Design and Installation, stationed in the Far East. He joined Westinghouse in 1967 as a Field Service Engineer, He has had varied assignments from steel and

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Mr. Farr is Chair of the CANENA THC 17A WG1 for Medium Voltage Motor Starters. Delegate for the US to the Working Groups Revising IEC 60470, IEC 60289 and IEC 60694 High Voltage, Motor Starters, Switchgear and Controlgear and Common Clauses.

He was appointed Westinghouse Fellow Engineer in 1988 and is Currently an Eaton Principal Engineer.



Arthur J. Smith, III was born in New Orleans LA July 4, 1955. He received his BSEE from Tulane University, New Orleans, LA in 1978.

He joined Waldemar S. Nelson and Company, Inc., a Consulting Engineering firm, in 1975 and is currently a Vice-President.

Mr. Smith is a Registered Professional Engineer in the states of Alabama, Alaska, California, Louisiana, Mississippi and Texas

He is a member of the IEEE, IEEE-IAS, NFPA 70 National Electrical Code, CMP-11, IEEE Standards Correlating Committee SCC-18, and IEEE P-1458 for the Recommended Practice for the Selection, Field Testing and Life Expectancy of Molded Case Circuit Breakers for Industrial Applications.