2016 TechCon® NORTH AMERICA

Advanced Dynamic Testing of Substation Apparatus

By

Voyo Mrdic and Raka Levi
DV Power, Sweden

TJ H2b ANALYTICAL SERVICES

Advanced Dynamic Testing of Substation Apparatus

Authors: Voyo Mrdic and Raka Levi
DV Power, Sweden

Abstract

This paper deals with two crucial apparatus systems in any HV substation: transformers with on load tap changer (including regulators), and modern HV circuit breakers. Advanced test methods like dynamic testing of circuit breaker arcing contacts, utilizing the most powerful source of 500 A, are explained. Condition of arcing contacts is clearly shown with high resolution using this test methodology without opening the breaker chamber. For a dynamic resistance recording, a DVtest of transformers during a tap changer operation, presented at previous TechCons [1, 2], special cases are addressed as learned from sites across the United States. Issues when testing voltage regulators and special recording algorithm for a unique construction with series transformer (booster) are presented. The paper shows some special cases of problems detected using these powerful diagnostic methods in the field.

Introduction

The most expensive piece of equipment in any substation is a HV power transformer. Its condition assessment has been a common practice for most utilities. Tap changer testing looking at the dynamic performance is a new way of verifying its performance. The dynamic recording of tap changer called a DVtest provides a great tool to asses its condition. At the same time, HV circuit breakers should perform their duty and disconnect the circuit, interrupt large fault current in case of a short circuit. This is carried by a particular component of a breaker – the arcing contact. Their evaluation is important to ascertain the next fault on the system would be interrupted within a specified period. Modern instruments provide excellent and safe tools for condition assessment of these apparatus. High power dc-dc converters provide up to 500 A for these types of tests. Of course, due to the inductance of a power transformer such high currents are not desirable for tap changer testing. However, high sampling rate of 10 kHz and powerful graphing and zooming capability of the associated software allows precise and easy diagnostics.

Circuit Breakers

The overall contact system of a modern circuit breaker consists of two distinct elements: Main contacts with a primary role to conduct currents when the breaker is in a closed position, and arcing contacts designed to be the first to touch and the last to part during its operation. Any electrical arc formed during the breaker opening or closing will happen on the arcing contacts. Their erosion under arcing condition is explained in the reference [3]. Testing them by injecting high dc current through the breaker contacts and simultaneously monitoring the voltage drop across the main contact during the operation of the breaker, a DRM test, was reported first in 1993 [4].

Today, modern instruments using a high frequency dc-dc converter as a power source generating several hundreds of amperes provide an ideal tool for this type of testing. Also, the DRM test requires a circuit breaker analyzer with a high-resolution measurement. The point of a position change from main to arcing contacts can be observed from the resistance plot. The resistance curve, as a function of a contact travel can be used to reveal potential problems related to the arcing contact condition [5]. At the same time, the actual length of the arcing contacts can be calculated as well as contacts overlapping if measuring the motion.

The interrupter consists of moving and stationary contacts immersed in insulation/cooling media – oil, SF6 gas, etc). Figure 1 shows moving and stationary contacts for a typical SF6 circuit breaker.

Main requirements from an interrupter are:

- To act as much as possible as an ideal conductor in the closed position;
- To act as much as possible as an ideal insulator in open position;
- To perform fast open / close operation with:
- Minimal damage to contacts
- Minimal over-voltages produced during those operations.

Contact material is subject to wear and erosion. That is an unavoidable consequence of a current interruption process and formation of electrical arc.



Figure 1. Moving and stationary contacts

Special attention should be paid to the selection of materials in the CB contact design. The HV CB needs to carry currents up to 4000 A (or even 40 kA for units installed in nuclear power stations), to withstand (up to 3 sec) and break currents of up to 100 kA with 250 kA peak under abnormal conditions. High temperatures created during the operation cause vaporization of the contact material which is the main reason for contact erosion. Experimental results obtained show erosion of the contacts made of heterogeneous (sintered) materials is significantly smaller than in homogeneous (pure metal) materials such as copper [6].

That is the main reason, overall, a contact system of circuit breakers consists of two distinct contact elements: Main contacts with a primary role to conduct current when the breaker is in a closed position, and arcing contacts designed to be the first to touch and the last to part. Any electrical arc formed during the breaker operation will happen on the arcing contacts. A design of modern high-voltage puffer-type SF6 gas circuit breakers is based on the switching of two

parallel contact sets. First, the low-resistance silver-plated main contacts are specifically designed to carry the load current without any excessive temperature rise. The second, tungsten-copper arcing contacts operate at the breaker opening following the main contact separation. The electrical arc starts after the arcing contacts separation. The tungsten-copper material is designed to carry the arc until it is cleared at the next zero–crossing.

Offline timing tests and static resistance measurement will provide only partial diagnostic information about the state of contacts. By definition, a circuit breaker timing test is a process of measuring the mechanical operating times. These tests are used to determine synchronization between phases, or within one phase for circuit breakers having more than one break unit per phase. Also, timing test on the circuit breaker can provide information about other crucial parameter – contacts bouncing. Arcing contacts are eroded much faster if undesired bouncing occurs.

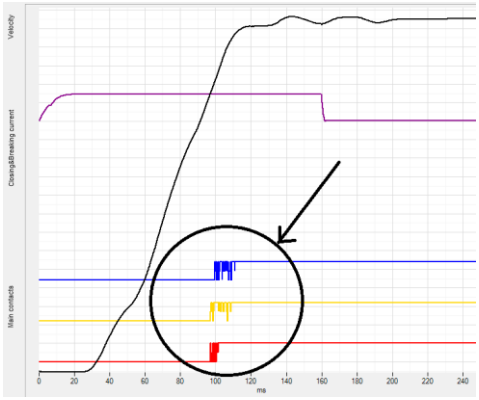


Figure 2. Increased contacts bouncing – timing test on SF6 circuit breaker 123kV, manufactured in 1970s

Several standards (IEC 60694, ANSI C37.09) suggest the measurement of circuit breaker main contacts static resistance as a part of standard offline diagnostic test procedure. Unfortunately, this test on the circuit breaker interrupter unit does not provide any information about the state of arcing contacts, as they are shorted by main contacts.

This is the reason a dynamic-contact resistance measurement (DRM) method was introduced as a tool to diagnose the condition of arcing contacts. The method is based on the breaker contact resistance measurement during an opening operation at rated contact speed using high power source.

Voltage drop measurement across breaker terminals using a Circuit Breaker Analyzer instrument (analog channel – range 1 V) provides a desired graph when a dc current is injected. The higher the current, the better the resolution of the graph. The graph in the Figure 3 is recorded with 500 A source.

A successfully used strategy was performing the DRM tests at rated opening speed while simultaneously injecting high current. The Circuit Breaker Analyzer and Timer was used as both: the power source, injecting the current, and a voltage drop recorder. Test object was 145 kV SF6 dead tank circuit breaker.

Technical characteristics of a 500 A micro ohmmeter used as a power source were: load voltage of up to 7 V, and measuring accuracy of ±(0.1 % reading + 0.1 % full scale).

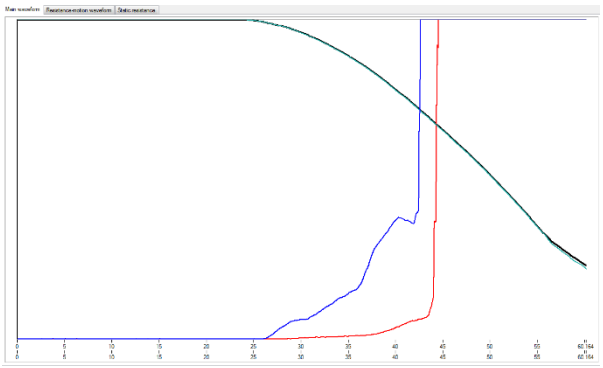


Figure 3. DRM traces of two phases – good one (red) and damaged arcing contacts (blue)

Linear to rotary converter was used for a digital rotary transducer, with transfer function: 1 mm at contacts = 2.79 deg at transducer. Measured static resistance of the breaker was 88.9 μΩ and this value shows no damage on the main contacts.

The DRM results obtained at 200 A current indicated the main contacts separation at 19.6 ms. It means the arcing contact overlapping time is approximately 5.2 ms which is the expected time, and overlapping length is approximately 20.6 mm. The measured length of arcing contacts is approximately 20.6 mm (57.6 deg), from 19.6 ms to 24.9 ms.

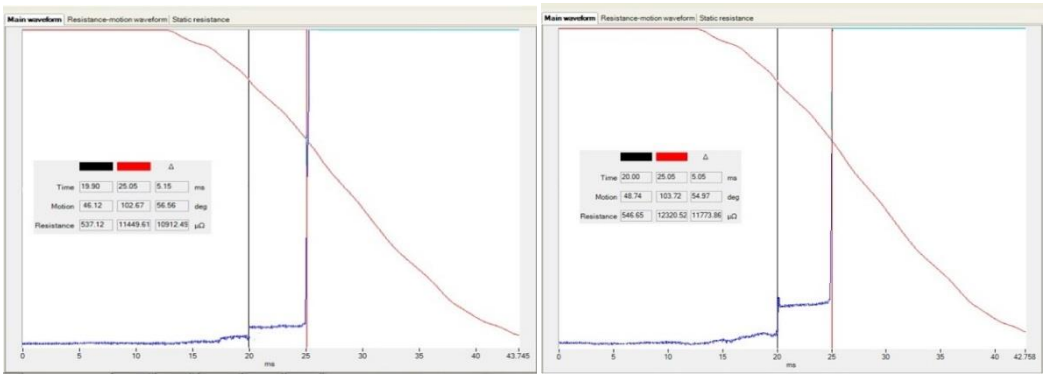


Figure 4. DRM graph at 100 A on the left and 200 A on the right, on 145 kV SF6 circuit breaker.

It is often difficult to identify the point of main contact parting. The main contact separation point is not as obvious at 100 A trace as in the second approach with 200 A. The graph at 200 A is far smoother and the point of main contact parting can be easily identified.

When the timing and motion results indicate an abnormality, the DRM test can be an effective way to further diagnose the internal condition of the breaker contacts. Based on the above discussion it becomes clear that interpreting the DRM curve at currents below 100 A may lead to a wrong diagnostic conclusion, especially for the main contact separation. As the injected current is increased from 100 A to 200 or 500 A, the graph is far smoother, any defects are clearly visible, and the main contact separation can be easily identified.

On Load Tap Changers

Tap changer is the only moving part under voltage in a power transformer. For that reason, its reliability is of crucial importance. Large number of tap changer failures take transformers with it [7], and their failure rate is between 20-40% [8]. Since 1995 a new test methodology has been utilized for OLTC condition assessment [9], a Dynamic Resistance Measurement (DRM). Finally, a tap changer can be evaluated based on its dynamic performance in the field, not only by checking the contact resistance.

DVtest of an OLTC

DVtest or a Dynamic Resistance Measurement is an off-line, non-destructive test in which a dc current is injected through a transformer winding and tap changer as it moves through all of its positions [1]. Results from the current signatures recorded at high sampling rate of 10 kHz are examined and compared against previous tests, or similar unit test results. This test on a regulator may be used to detect problems such as tap changer slow transition time, contact problems, and open circuits among others [2].

Series transformer

Series transformer or a booster is a separate three phase transformer placed in the tank of the large power transformer itself. It is an independent circuit, magnetically coupled to the secondary winding, and the voltage is regulated by inducing positive or negative voltage through the series transformer. The tap changer is connected to the tapped winding which is magnetically coupled to the main transformer winding. Consequently, the tap changer has no electrical contact with any of the transformer bushings.

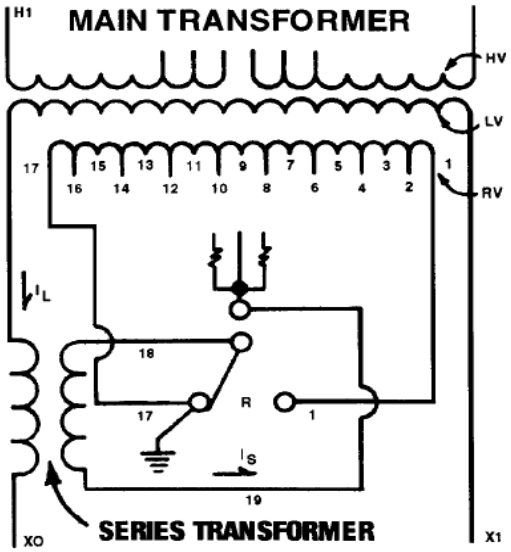


Fig. 5: Schematic of a tap changer with a series transformer

The Figure 5 shows a diagram of a resistance-type tap changer with a series transformer. However, reactance-type tap changers can also utilize series transformer. Because the transformer low voltage side has higher nominal currents than the high voltage side, it can be challenging to make a tap changer for the LV side. If the secondary circuit requires the tap changer to switch higher currents, some manufacturers opt for a series transformer. Usually, the borderline is around 600 A.

To reduce a current tap changer switches, it is placed in the same circuit with a series transformer. The current in this circuit is several times lower than a current in the transformer LV side. This is achieved by increasing a voltage of the regulating winding (marked RV in the Fig. 5) compared to required regulation percentage.

DVtest When a Series Transformer is Present

If the tap changer is placed within the series transformer circuit, it is impossible to inject and measure the current through the OLTC. Therefore, DVtest (DRM) cannot be performed using a standard procedure. Instead, DV Power offers its newly developed proprietary procedure. The DV-Win software that controls the instrument has a special panel for "series transformer" testing. This mode includes several additional parameters, like "Voltage change" in percent and "Time after motor start" in seconds, as it will be explained in the following text. Once the tap operation is detected, a signal, similar to a radar beam, is sent and a reflection is recorded on the test current trace.

Since the tap changer is only magnetically coupled with the secondary winding, a steady dc current in the winding under a test will neither create any variable flux nor induce a current through the tap changer circuit. To create a current flow through the tap changer, it is necessary to provide a variable dc current value through the secondary winding. This creates changes of magnetic flux and generates a current in the tap changer circuit. Any change in this current, such as change/ripple during transition, will be reflected through the series transformer into the secondary winding DVtest (DRM) current that is being recorded.

The variable DVtest current is generated in the following way: during each transition, the test voltage, and therefore the test current, is automatically decreased for a predefined percentage ("Voltage change") after a predetermined period ("Period after the motor start"). The test voltage (and the test current) is maintained at this lower value for 5 seconds. During this time window, the user should observe a ripple graph. The waveforms will have different shapes depending on the inductance and other parameters of the transformer [10]. Adjusting those two parameters in the software will make the ripple more pronounced, and easier to analyse.

DVtest Graph Analysis

In general, the ripple is minuscule compared to the current drop created by the algorithm, as can be seen in the graph of the Figure 6 below.

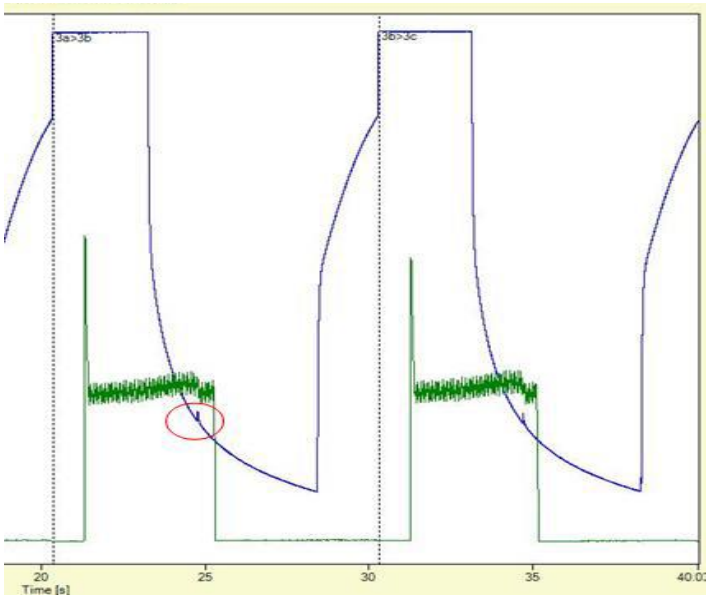


Fig. 6: Series transformer DVtest graph, a transition is marked with the red circle, motor current in green

The ABB tap changers UZERT are "resistive types" where resistors are inserted in the circuit during the transition from one to the other tap position. During the "series transformer" special test procedure, each transition creates a reflection in the main test circuit, as shown in the Figure 7. A mirror image of the transition graph is evaluated by observing the graph shape and transition times. The transition time comprises of three segments: resistor R1 carries the load, resistors R1 and R2 carry the load in parallel, and the resistor R2 carries the load, before the main contacts make firm connection. On the DVtest graph it can be easily observed where the current goes into recovery. Tap changer contacts' resistance cannot and should not be measured because the tap changer is not in the electric circuit of the test loop [10].

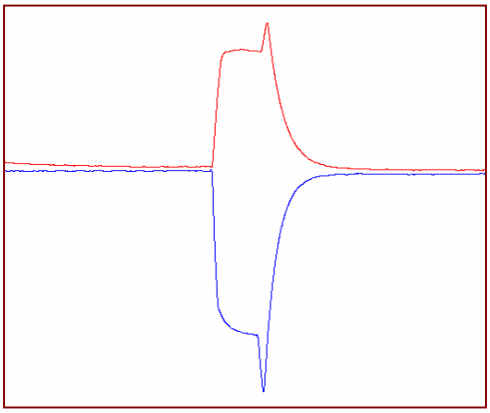


Fig. 7: Regular transition (blue) and the mirror image (red)

The Figure 8 shows a complete graph of the DVtest (DRM) on one phase of the power transformer. The ripple changes its direction from lower taps to higher taps. It is not a surprise, although normally a ripple develops in the same direction. This may be attributed to two processes. The first is the DC current stabilization of two separate windings – the secondary winding of a power transformer, and the series transformer circuit with the tap changer. The second is change of parameters of the series transformer circuit as taps are being selected, changing the time constant [L/R] of the circuit.

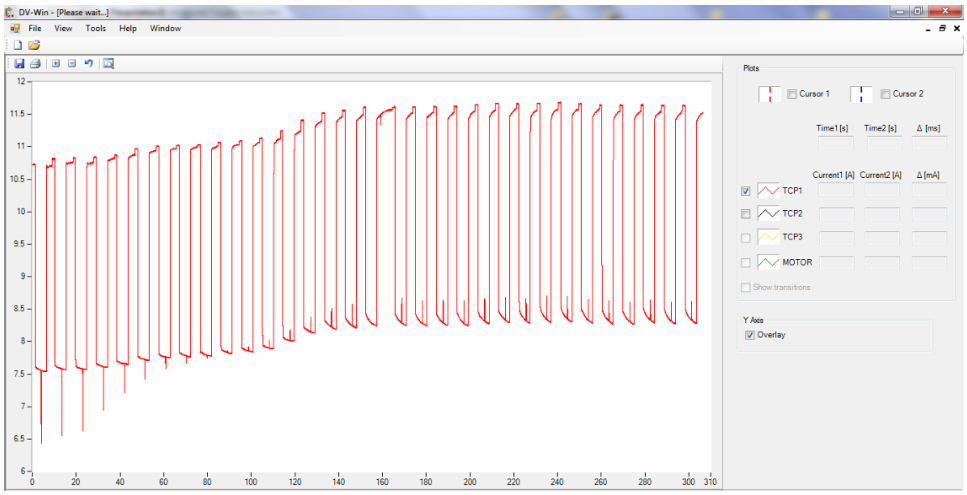


Fig. 8: Complete DRM graph of phase X1-X0 with series transformer

Finding a Problem

As DVtest (DRM) is a new methodology, and a small database of signature graphs exists. For that reason, the evaluation is based on comparison of ripples between transitions. This is done on a resistance-type tap changer between all ripples, while for the reactance tap changers odd ripples are compared to odd, and even ripples are compared to even ones. This is due to the inherent bridging and non-bridging tap positions the reactance tap changer operates through.

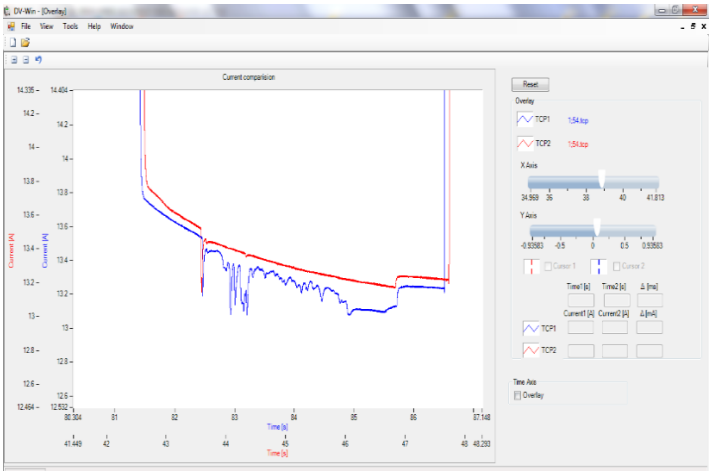


Figure 9. Bad (blue) and good (red) DVtest traces

Figures 9 and 10 show two ripples, red and blue, where one is a clean trace while the other shows disturbances symptomatic of a bad contact – wear, bouncing or even coking.

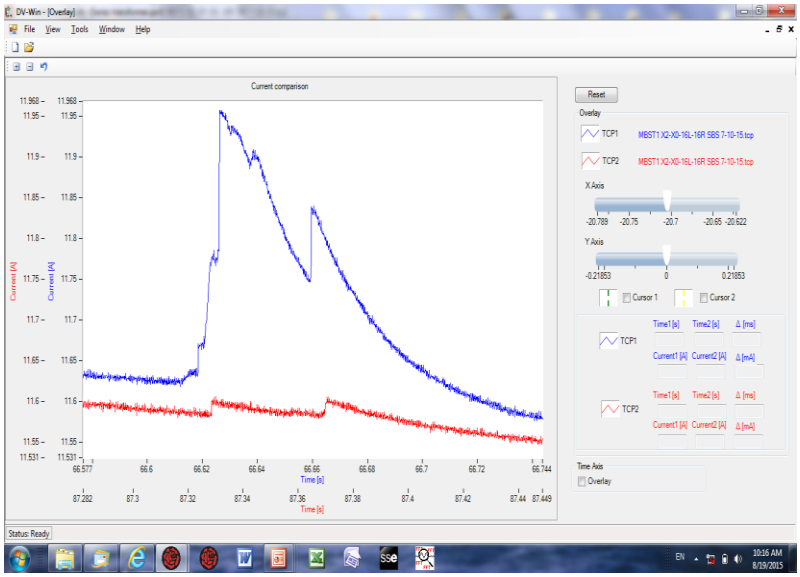


Figure 10. Good (red) and bouncing contacts (blue) trace

One benefit of testing a three-phase power transformer is the fact that traces of DVtest (DRM) graphs can be compared among the phases, and any deviation is an indication that the tap changer may be performing badly.

Voltage Regulators

Regulators are regulating transformers, or more precisely regulating autotransformers. Some utilities do not like to put their expensive power transformers in danger of failing by placing a moving component - tap changer (OLTC) - in the main tank. Others have a need for voltage regulation closer to the load, and for that reason we find many high power regulators in the US networks. Most of them have 33 positions and regulate the voltage +/- 10%. The most common configuration is to provide 16 steps of 5/8% (0.625%) each, in both raise and lower position.

Regulators can be divided into large three-phase units, and smaller single-phase units. While three-phase units have all the characteristics of an autotransformer with a normal tap changer, smaller ones may have special design with super fast tap changers; some for example operate within 250 ms. In other words, that regulator can change 4 tap positions within 1 second, see Figure 13.

As one side of the regulator is called SOURCE and the other LOAD, the voltage is varied at either side as required. The neutral point/bushing is usually called SL or S0L0. Type A regulators as per ANSI standard vary the voltage at the Load side while keeping the Source voltage constant, while type B does inversely, and is called inverted design, as it changes the Source voltage while the Load side is kept constant. See Figure 11 for comparison of type A and

B regulators. This is achieved by placing the tap changer in the Load or in the Source side. That will be important when deciding how to test a tap changer in a regulator.
One big difference in their design characteristic, compared with an autotransformer is the resistance and inductance at the tap changer neutral position. The winding resistance of the neutral position can be down as far as 2 mΩ level, while the end tap would measure 10 times resistance of the neutral tap. This is due to the fact that at the neutral position we have regulation of 1:1 and no regulating winding is in the circuit, only tap changer contacts and connections. At the extreme tap positions we have full regulating winding in the circuit as seen in the Figure 11.

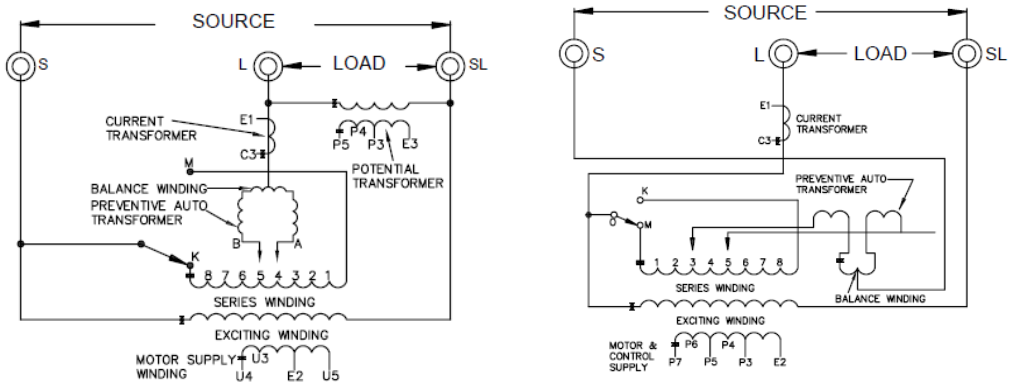


Figure 11. Schematic of two single phase regulators: type A (left) and type B

DVtesting Tap Changer of a Regulator

The DVtest or the dynamic recording of the test current provides very different overall graph compared with transformers. Ripples, the key DVtest features indicating a tap changer operation, are changing from small to very large value at the neutral position (see Figure 12), and then getting smaller again as other extreme position is approached.

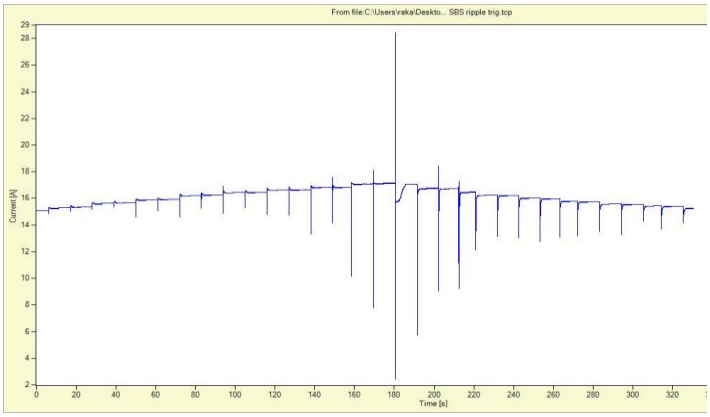


Figure 12. DVtest graph of a typical regulator

Regulators can be equipped with tap changer of either reactance or resistance types. The reactance types are predominant in the USA networks. Ripple shape of a DVtest graph is

characteristic for each construction of the tap changer. Regulator ripples are very much the same shape but different magnitude of their transformer counterparts. For that reason, during the result evaluation, attention should be paid to the type and manufacture of the tap changer itself. The Figure 12 graph shows different ripple shape for transitions before and after neutral position. This is normal for some reactance type tap changers.

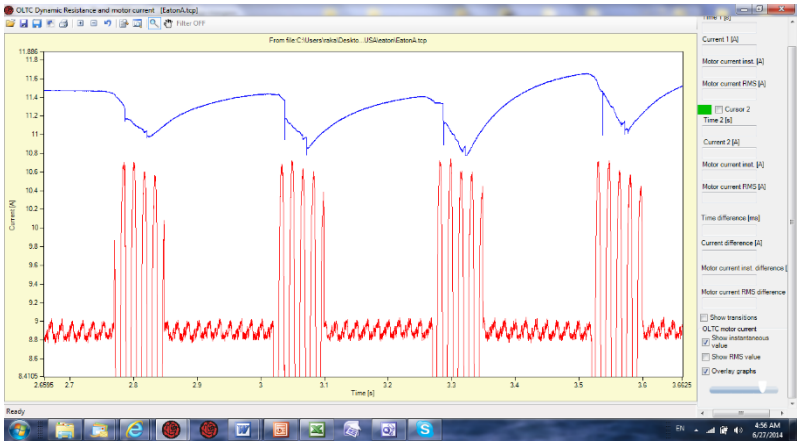


Figure 13. Four transitions in one second of a fast regulator

Three-Phase Regulators

DVtest on a three-phase regulator may be performed using a single-phase instrument or a three-phase DV Power instrument like TWA40D [11]. The three-phase instrument allows connecting all bushings at one time, and then we would consider S (source) side as the HV side, and the Load side as a LV or secondary winding. Both neutral test leads are connected just like for an autotransformer, to the S0L0 bushing.

Test should be performed this way to include the tap changer. Three-phase instruments provide for three options: LV, HV, and BOTH [11]. Selecting the appropriate option requires reading and understanding the regulator nameplate schematic. Of course, for investigative tests one can use the three-phase instruments in a single-phase test mode and perform any type of connection permutation.

Single-Phase Regulators

Performing a test using one of the single-phase DV Power instruments allows for selecting connection of test leads the way we want. Normally one lead would be connected to the S side, while the other to the L side. Alternatively, one would be connected to the SL terminal – but then attention should be paid that the tap changer is indeed in the test loop (see comment about A type and B type). If not, the graph obtained would be just a straight line.

Testing between S and L has one disadvantage: very low resistance and inductance of regulating winding only, while testing between "SL" (neutral bushing) and S or L terminal includes the common winding in the test loop, and makes the ripple smaller and response time different.

A specific issue at neutral on regulators is slow recovery time. As the test is performed using dc current, the inductance of the regulator winding, once introduced in the test loop following the neutral position (where inductance is zero), makes current increasing very slowly. This is visible on the graph of the Figure 12 in smaller degree, while at Figure 14 it is extreme.

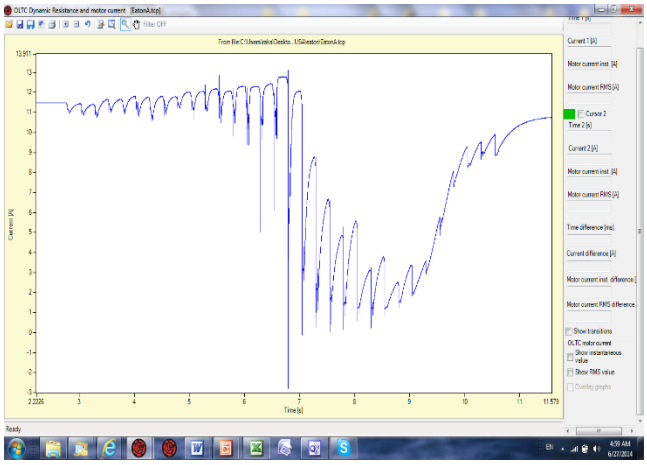


Figure 14. Slow recovery after neutral position

Graf in Figure 12 is of a slow tap changer, recorded by waiting for a few seconds between transitions. The Figure 14 graph, however, was recorded with high speed regulator, where transitions last very short and time to re-establish current after changing taps through neutral position is few seconds. This is significantly longer than it takes to switch from neutral (position 17) to 33; for this particular regulator about 4 seconds.

Following any of the procedures described above, various types of tap changer defects can be detected, just like on a regular power transformer as described on various cases in reference [2].

Conclusion

Advanced dynamic testing provides a great tool for performance evaluation of "moving" apparatus. Those are circuit breakers and tap changers in transformers. With sophisticated instrumentation providing high power and fast recording possibilities, we can see the dynamic operation of HV power apparatus. DV Power Sweden is producer of the most sophisticated instrumentation for condition assessment of substation apparatus. Ability to produce high power from a low weight instruments brought a new era in the substation testing. Both apparatus types discussed above have been tested using our powerful instruments over the past few years, providing a perfect insight into its dynamic condition.

References

1. R. Levi, B. Milovic, “OLTC dynamic testing”, Proceedings TechCon USA, San Francisco, Feburary 2011

2. R. Levi, G. Milojevic, “From the AMforum Knowledge-base: Case studies of OLTC problems detected by DVtest”, TechCon – Training Track presentation, Sacramento CA, February 2015

3. A. Secic, B. Milovic, “Dynamic Resistance Measurement Method Applying High DC Current”, CEATI WS, Palm Desert, CA, USA, 2014

4. F. Salamanca, F. Borras, H. Eggert, and W. Steingraber, “Preventive diagnosis on high-voltage circuit breakers”, Proceedings CIGRE Symposium, Berlin, Germany, 1993, pp. 120–02.

5. J. Levi, R. Ostojic, "Use of micro ohm meter as a power source for DRM testing on dead tank circuit breakers ", Doble client conference, Boston 2013

6. M. Kapetanovic, "High voltage circuit breakers", a book, Faculty of Electro technical Engineering, University of Sarajevo, 2011

7. WECC substation working group meeting minutes, Vancouver WA, USA, May 2006

8. Transformer failure causes in Germany, IEH Liebnitz University Hanover – Shering Institute, Institute of electric power systems, Division of high voltage engineering

9. H. F. A. Verhaart, “A diagnostic to determine the condition of the contacts of the tap changer in a power transformer”, CIRED, Brussels, Belgium, 1995, paper 1.13.

10. DV Power, Application note: “DRM Testing With Series Transformer Present in OLTC”, Lidingö, Sweden, 2015

11. DV Power, “Tap changer and winding analyzer TWA40D”, brochure B-W040DN -305-EN, Lidingo, Sweden 2015

Biographies

Voyo Mrdic has been working as an applications engineer in transformer testing group at DV Power, which is well-known manufacturer of test and measurement equipment for electric power industry. He is a product engineer for the three phase turns ratio group of instruments. His responsibilities include development of new methods for transformer testing, providing technical support to DV Power customers, as well as performing on-site field testing. Voyo performed numerous tests on transformers in substations throughout Europe and Far East. Before joining DV Power 5 years ago, he had been working at the large apparatus manufacturer Energoinvest RAOP for 1 year as a junior engineer in circuit breakers and instrument transformers development department. Voyo has a diploma degree in electrical engineering from the University of East Sarajevo in Bosnia and Herzegovina.

Raka Levi, application expert, DV-Power Sweden, and convener of the AMforum association and Working group on DRM for OLTC. Raka has 30 years of asset performance and condition assessment experience, specializing in apparatus testing, monitoring and diagnostics. Six years ago he started within the AMforum organization a working group on DRM test methodology for tap changers. He has been running committees that assemble asset managers and operations specialists of major European utilities since 1995, organizing conferences in Europe, TC Universities in the USA, and TC Colleges in Asia.

He has written over 20 technical papers on the subject of electrical testing, transformers, OLTCs, and breaker diagnostics and condition monitoring. Raka has a Dr.Sci. degree in the field of HV diagnostics for circuit breakers and Diploma of electrical engineering, both at U. of Belgrade, and ME in electric power from the RPI, New York.