Condition Monitoring of On- Load Tap Changers using Vibration Analysis

By

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Abstract

For many years On-Load Tapchangers (OLTCs) have been a common source of failures on Power Transformers. Power Utilities have implemented various condition monitoring techniques that have been more reactive and preventative than predictive in their approach. This has been largely to do with the available techniques for monitoring the tapchangers.
By the nature of their operation, OLTCs generally deteriorate at a greater rate than the main transformer and so the ability to detect a potential fault has largely eluded asset owners. The Queensland University of Technology (QUT) in Brisbane developed and tested a device that records the vibrations emitted when a tap change occurs, analyses the data and by using of a mathematical model can identify potential problems within the OLTC.
This paper describes the method of application and operation of the device, outlines how the data can be interpreted to identify potential problems and the types of problems that can be detected.
The device is not yet commercially available and this paper goes on to describe what results have been gathered in the past as well as the work that is being undertaken to bring this device into commercial reality.

Introduction

Condition monitoring of OLTCs has been less than satisfactory for many years with the time proven options of oil analysis and internal inspections during periodic routine maintenance. Taking oil samples for DGA can give a limited amount of information and generally at a predetermined point in time. This information is generally associated with high resistance joints, significant contact and braid wear and other internal tapchanger problems. It does not consider nor can it detect such areas as the causes of mechanical failures ie spring tension, Geneva wheel wear, drive shaft wear and so on. These mechanical components are additional causes of failures of tapchangers.

The Queensland University of Technology (QUT) in association with the Queensland Electricity Transmission and Distribution (QETD) companies developed a no-intrusive technique that monitors tapchanger tank temperature and vibration, main transformer tank temperature, other component vibrations and the drive motor starting current. Subsequent mathematical analysis provides information about the degradation of the OLTC over time using real-time techniques. Simply put this technique allows not only a non-intrusive insight to the tapchanger condition but the information can be gathered intermittently, continuously and without interruption of supply.

The information obtain from monitoring in-service transformers proved to be of great value and allowed a detailed analysis of the vibration waveshapes to be compared with actual maintenance on the tapchangers. Whilst the data collected to date has been from one type of tapchanger the further research being done at Ergon Energy intends to collect data from a range of tapchanger types so that baseline data can be obtained for engineers to use for comparison with results they obtain from their network assets.

How a Typical Bolt-On Resister Style OLTC Operates

To fully understand the method by which the system described in this paper gathers specific data it is important to review the operation of a resister style on-load tapchanger.
Figure 1 shows the sequence of operation when changing under load from Tap 8 to Tap 7. When a signal is received at the control cubicle the tapchanger being on Tap 8 (position (1) below) will begin to move to Tap 7. Generally the time taken for a change in tap position from one contact to another is around 50 milliseconds but the entire cycle can take some 5 to 6 seconds to complete [(3)(1)]. The first stage of the change is when the transition resistor contact (normally a roller contact) moves to make contact with Tap 8 as seen in position (2) of Figure 1 below. When this occurs the transition resistor roller contact is short circuited and all load current continues to be carried by the solid contact. When the solid contact moves or breaks away from Tap 8 as per position (3), the load current is then carried by the transition resistor. When the break occurs there is a low level of arcing between the fixed and moving contacts. As the tapchanger continues through the sequence to position (4), the solid contact makes with Tap 7 and again a small amount of arcing occurs. At this point the transition resistor roller contact is short circuited and the load current is again carried by the solid contact. As the tapchanger completes the cycle the contacts continue to move to Point (5) where the transition resistor roller contact is once more out of circuit.

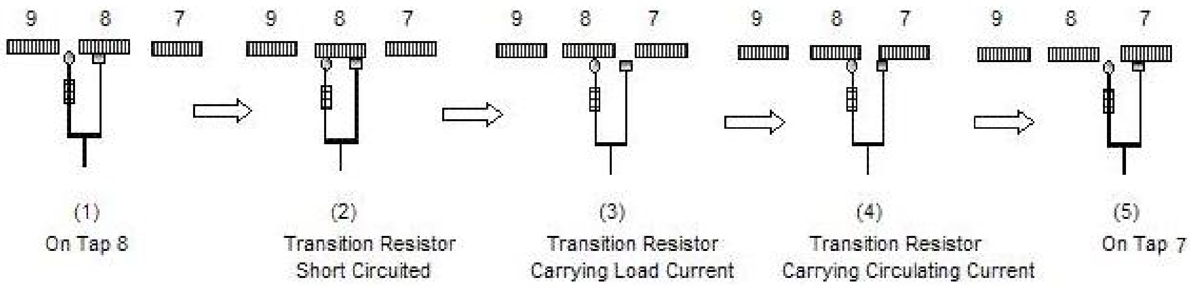

Figure 1
Switching sequence of resistor type tapchanger

Whilst the above gives an insight to the switching sequence without the motor drive mechanism and control cubicle operating at their optimum then numerous mechanical faults can occur and cause a catastrophic failure of the OLTC. The motor drive components include the drive motor, reduction gears, charging springs, the Geneva wheel, shaft couplings and the drive shaft, as shown in the simple diagram in Figure 2 below.

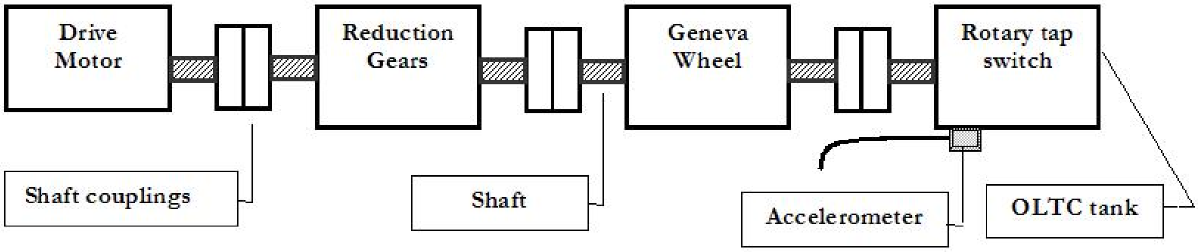

Figure 2 (2)
Representation of an OLTC motor drive mechanism

During each step in a tap change the making and breaking of fixed and moving contacts results in arcing and contact friction and wear. These together with the charging of the spring mechanisms, rotating of the Geneva wheel and cams, the operation of the motor and the motor drive shaft, emit a variety of vibration/ acoustic signals which can be detected with simple accelerometers. By gathering these signals we can analyse the data over time and detect changes in the waveshapes that directly relate to component wear.

It is important to remember that the tapchanger is normally the only mechanically operated component on a transformer and if not maintained correctly it will like all mechanical devices ultimately have a component failure. History of failures caused by lack of maintenance, misaligned contacts, failed or broken parts is well documented and the costs to the asset owner can be extremely high.

The OLTC Monitoring System

The system developed by the QUT operates on a very simple basis; it logs data from currents, vibrations and temperatures then processes the data and analyses the waveshapes. The outcome is a filtered set of data that can be used to compare against "footprint" data to determine any changes in component signatures. These changes can be analysed to determine if they are of concern. The variations in the waveshape amplitude and time give different meanings to component conditions and rate of deterioration. As indicated by the speed of operation of the tapchanger the time to record the data is very short and as such a very fast sampling frequency is needed. It should also be noted that there are significant differences in the frequencies of the signals being recorded. For example, the vibration signals of the contacts during a tap change are high frequency whereas those from the motor drive are at much lower frequencies. The temperature signals are purely DC signals and need very little manipulation. The system has been designed to manage all these variations in real-time.

To show how the monitoring system works a simple schematic diagram of the main components is shown in Figure 3 below. The system hardware consists of a transducer module, a signal pre-amplification module, a signal condition module, a data acquisition module and computer. The entire system is electrically isolated so that it can operate under adverse substation environments. It can be triggered manually or automatically thereby allowing off-line data capturing manually and automatic on-line data acquisition.

The main tank temperature, load current, OLTC tank temperature, tap position signals, drive motor current and the OLTC tank wall vibration signals are taken to the signal condition module where it is converted to appropriate digital and analogue voltage signals for input to the data acquisition module. The computers operate LABVIEW [12] to record signals whenever a tap change occurs. This way the operator can view the data immediately as the analysis of signatures are done on-line automatically and following data filtration, the useful information from the signals are stored for daily transmission to a remote location.

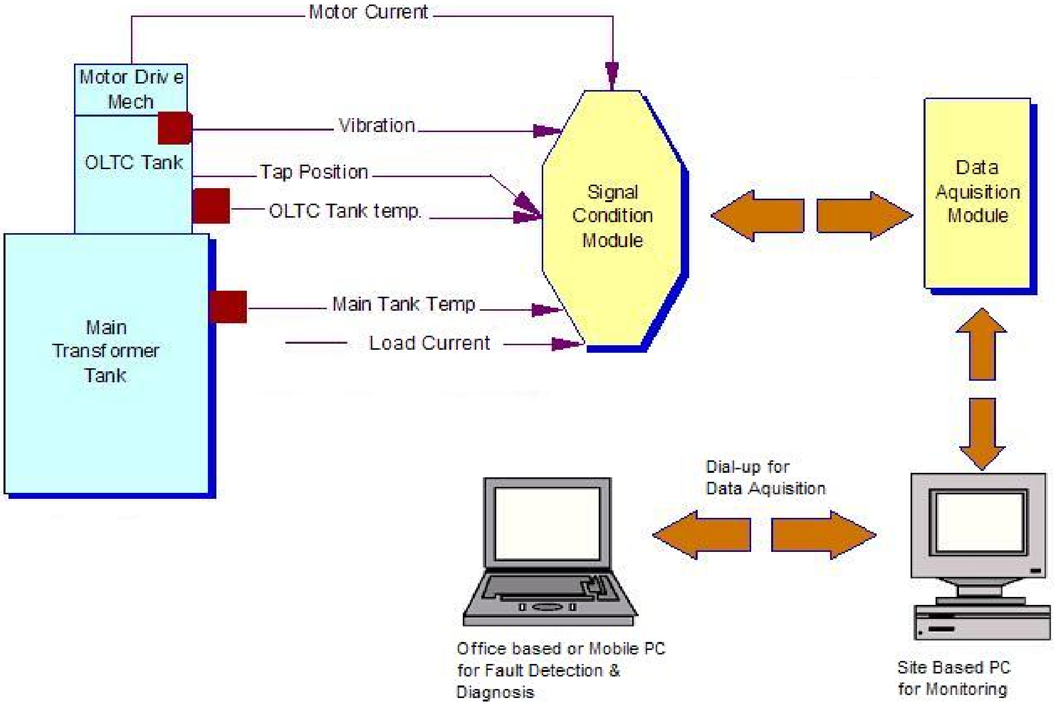

Figure 3

OLTC Monitoring System

Some of the information can be used without further processing e.g. the total number of tap changes and the tap operating range. Whilst these are often recorded by other instruments as well, it is important to log this information so that the system can learn the operating patterns and provide the operator with clear warnings of an impending fault.

The rise in temperature of the OLTC tank above the main tank also provides direct indication of developing problems in the OLTC. Just as we do with the main transformer we can set limits to the temperature rise of the OLTC tank. It has been found that a temperature differential of less than $15^{O}C$ between the tanks is common and generally the OLTC is operating normally. However, if the temperature differential is greater than $15^{O}C$ then there may be cause to investigate using additional condition monitoring techniques such as DGA and particle analysis [7]. It should be noted that some tapchangers can be operating normally with temperature differentials of more than $15^{O}C$ without any detrimental effects.

The magnitude and duration of the motor starting current and normal motor current provide information about the condition of the OLTC motor and spring charging system.
The times between the vibration transients provides information about the speed of the tap change operation and an indication of the condition of the spring driven drive train.
Normally without routine inspections by specially trained maintenance staff particular wear patterns on the drive train may not be picked up and failures may occur without apparent warning. The system can observe abnormal vibrations which can indicate incorrect shaft alignment, spring tension changes, abnormal wear on the Geneva wheel and so on. Vibration analysis of electro-mechanical apparatus such as electric motors and generators has over the years been proven to be successful and therefore the application to tapchangers is somewhat like an extension of that technology.

Connection to the Transformer and Tapchanger

Often the problem with using condition monitoring equipment is that the transformer must be taken off-line to fit the components. This is not always convenient as the transformers that most need the monitoring are those that are least accessible or cannot be taken out of service due to their criticality. The components in this system can be easily retrofitted to bolt-on style tapchangers on transformers in the field and in most cases the transformer can remain on line.

Figure 4 below shows a schematic diagram of the hardware for the monitoring system. The signal conditioning module connects transducers mounted on the transformer to the monitoring computer. The external connection box is mounted close to the transformer and the clip on CT is connected to one of the phases of the OLTC motor to provide an input to the box. The 30 kHz miniature vibration accelerometer is fixed to the bottom of the OLTC tank in a position that is likely to give maximum signal strength and then connected directly to the connector box.

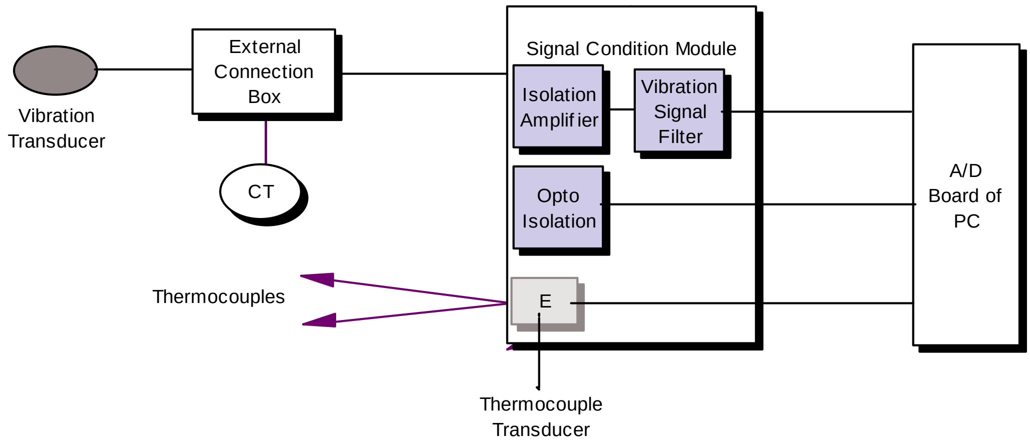

Figure 4
Schematic of OLTC Monitor Hardware

This remote connector box contains a vibration signal amplifier board and provides a constant current signal to the piezo electric accelerometer. The outputs from the connector box are fed into the main signal condition module via multi-core cables. In the signal condition module, the receive signals are passed through an isolation amplifier which protects the monitoring equipment against possible transformer tank potential rises. The output from the amplifier then enters the vibration signal filter board where the signal is rectified and smoothed before it is sent to the Analogue/Digital board of the monitoring computer. The opto-isolation unit provides input so that the digital inputs from the tap position indicator can be sent to the A/D card on the computer and finally the thermocouples are connected to the OLTC and transformer tanks and the transducer from which the signal is sent again to the A/D card.

At the computer the user can interrogate the system locally or remotely, modify the settings according to the type of tapchanger and desired information outputs. Figures 5 and 6 below show the user interface of the on-line monitoring system.

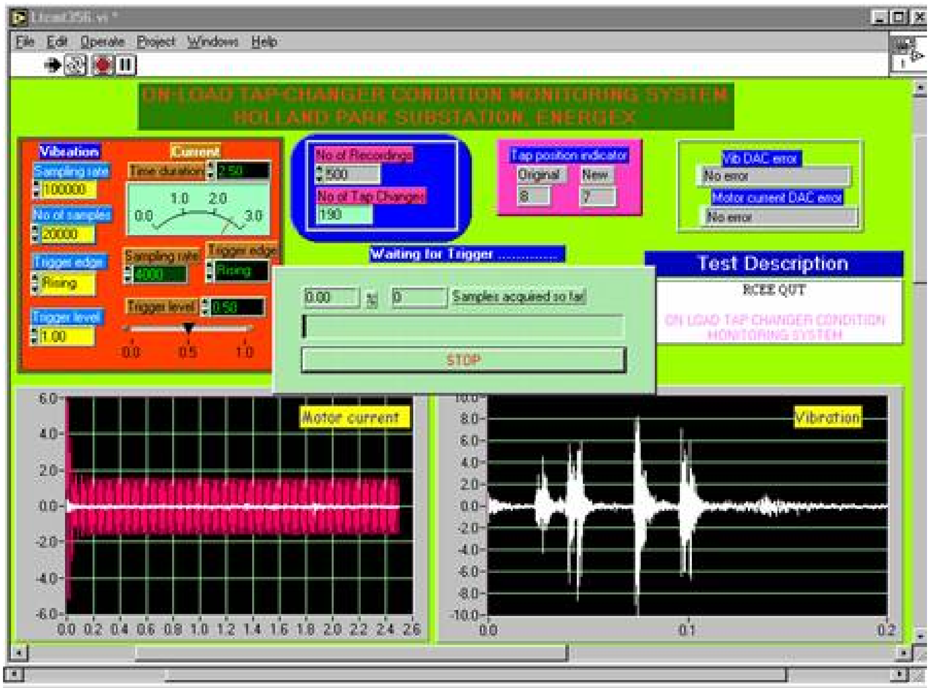

Figure 5
User Interface Screen [4]
Displaying motor current & vibration measurements

Figure 5 shows the motor current and vibration measurements of a tapchanger operation. The small pink box at the centre top indicates the old and new tap positions. The blue area shows the number of recordings taken and the number of tap changer operations. On the top left of the screen are the sampling controls and indications of the vibration sampling rates and number of samples along with details of the time durations and currents. The vibration bursts in the bottom right hand corner of the screen show the sequence of operation from initiation of a change to completion. Each burst identifies a different component as it operates and an in-depth analysis of each burst will give detailed information on the condition of that component. Finally the red waveshape on the left shows the motor current during the tap change.

Figure 6 show a secondary screen that provides data on the temperature changes between the main and tapchanger tanks over time. The time interval for measurements is set in the top left hand box along with the tap position indication. The centre top of the screen is a quick reference “Thermometer Style” display of the tapchanger and tank temperatures. This quick reference can show the temperature variations at a point in time where as the temperature plots on the graphical display on the bottom are more useful as an indication of the rate of rise of the variation. This bottom graph shows OLTC at the top, next is the main transformer tank, with the tap position second from the bottom and the temperature differential being at the bottom.

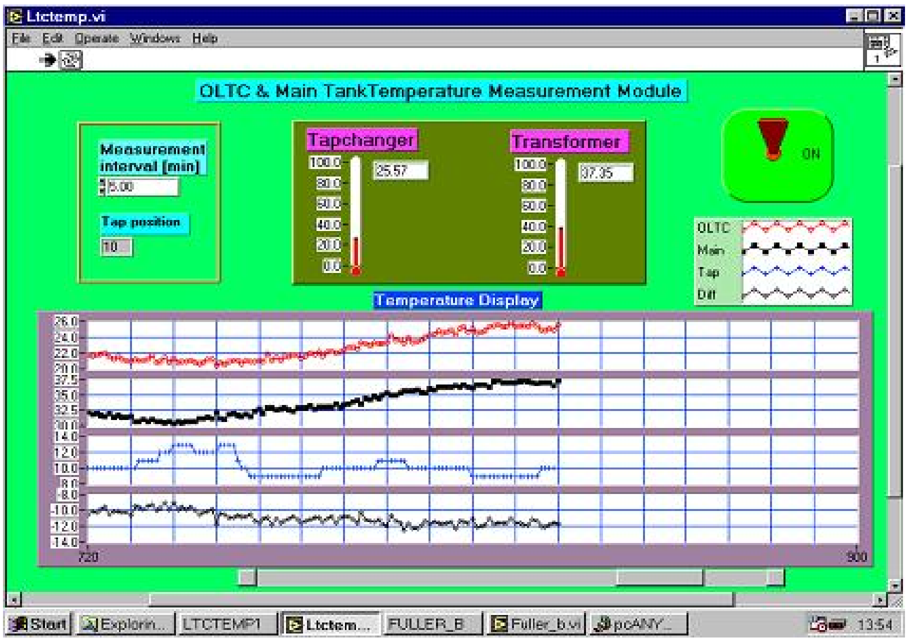

Figure 6
Main PC Screen display of Measured Tank Temperatures

This display is important as it gives clear and concise information about the temperature conditions of the taps not only during a change but also when the contacts are under load. As previously mentioned, if the temperature variation moves outside the normal operating range, then an investigation into the possible cause may be warranted. This display also has the added advantage of allowing the engineer to see the effects of system load conditions on the transformer temperature rise. The information is best used however in the early detection of high resistance connections that may be caused by worn or misaligned taps.

Detection and Analysis of Abnormal Vibration Signatures

The vibration signals detected when a tap change occurs gives a series of well defined vibration bursts as seen on the screen in Figure 5 above. The procedure developed can

automatically determine the times between the main vibration bursts. These bursts are caused by mechanical events such as contacts striking together and to a lesser extent electrical arcing at the points of making and breaking of contacts.
By using data collected and filtered, in conjunction with simple rules from site tests and inspections, the operator can soon determine such information as:

- Contact wear – both fixed and moving contacts – including wear profiles over time
- Drive shaft wear, misalignment or slipping
- Broken components.
- Bearing wear
- High resistance joints or over heating problems

The normal vibration signature emitted when a tap change occurs can be seen in Figure 7 below. In normal situations there are 4 vibration bursts which are produced by: (1) the drive motor starting, (2) the operation of the auxiliary contacts in the control cubicle, (3) tap changer contacts moving between taps, and (4) the operation of the brake motor.

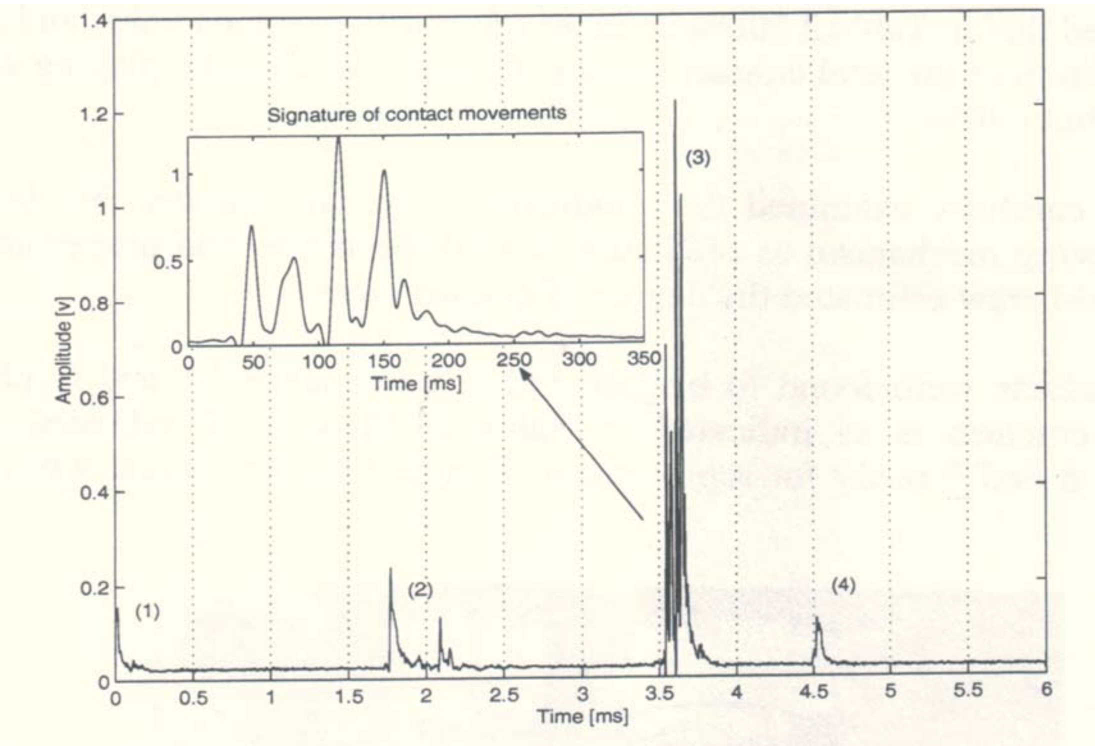

Figure 7[5]
Normal signature for OLTC

In each case a more detailed analysis of each wave shape can be made and this can reveal more specific data about the condition of the apparatus operating at a point in time. The initial data collected is difficult to analyse in the time domain due to the noise within the signature. Therefore to get the detailed analysis the signals are transformed from the time and frequency domains into the wavelet domain where the main components of the signal can be easily extracted. However, in Figure 7 we have remained in the time and frequency domains but taken the tapchanger contact signature and exploded the view to show more of this detail. The data can be collected for each tapchanger and considered to be a footprint for that tapchanger. It should be noted that each tap position can have a slightly different signature and it is important to take initial readings across the entire tapping range. The taking of more than one set of data is needed to ensure the accuracy of the data as it is possible that the signature can vary slightly depending on the direction of the change i.e. Tap 7 to Tap 8 versus Tap 8 to Tap 7.

If we relate the switching sequence shown in Figure 1 to the Signature of Contact Movements shown at point 3 of Figure 7, then in Figure 8 below, point A is where the roller or transition resistor contact makes with tap 8 fixed contact. Point B is where the solid contact breaks from tap 8 allowing the roller contact to take the load current. At Point C there is high amplitude due to the solid contact making with the fixed contact of tap 7 and to complete the sequence at Point D the roller contact leaves the tap 7 fixed contact.

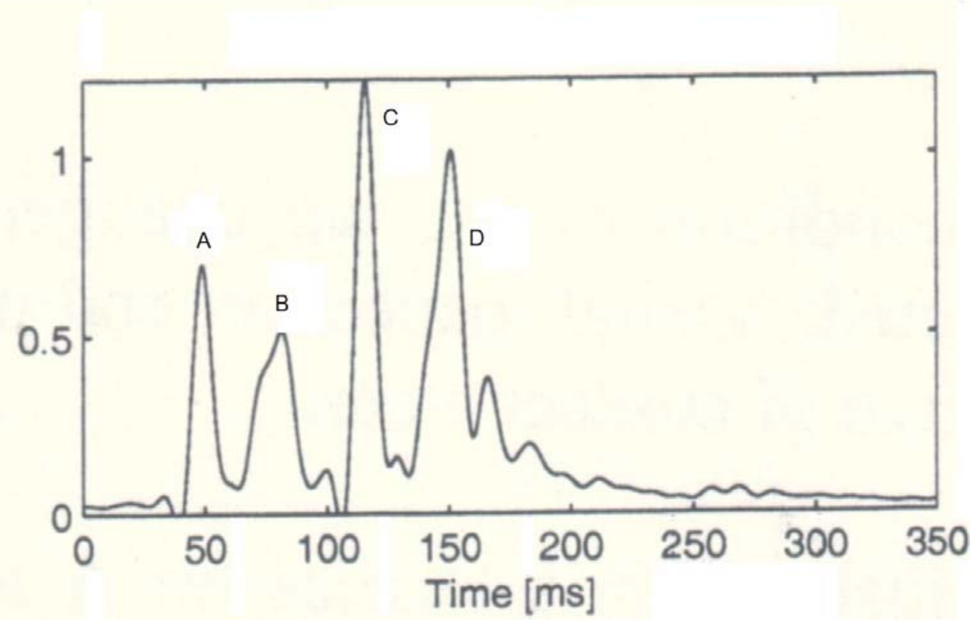

Figure 8
Signature of Contact Movements

In service abnormal signatures occur over time due to normal wear and tear. The rate of change of the signature is monitored so that the engineer can predict when the tapchanger is in need of maintenance. There are also many instances where a problem has developed in a tapchanger that does not fit in the normal wear and tear profile. Figure 9 below shows an example of this.

Here we see that in the exploded view of the contact movement, one of the 4 bursts is missing and there is a 5^{th} significant burst approximately 0.5 seconds after the tap change operation. In this case additional data across the tap range was taken and the additional burst was found to be on all tap positions, leading to the conclusion that it is not related directly to contact wear but instead part of the drive mechanism.

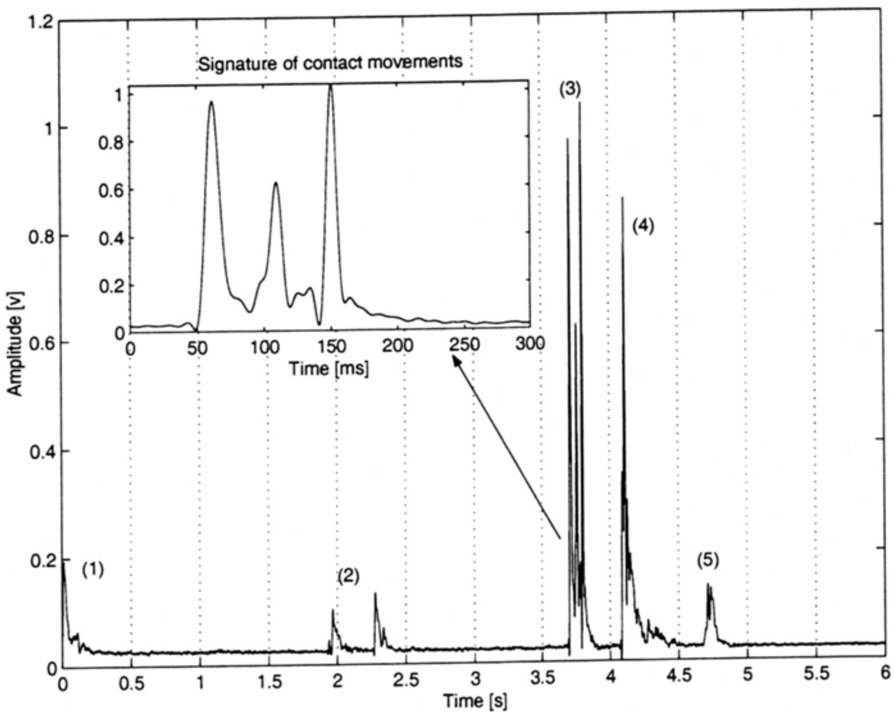

Figure 9 [(5)]
OLTC tap change with abnormal signature
An additional burst detected

This signature shows a number of other trends. At point (1) the drive motor starting appears to be within the normal operating range. At point (2) there is a change in the signatures produced by the auxiliary contacts in the control cubicle in both the time and frequency domains. This change indicates a possible delay in the time of operation and could be related to the drive shaft timing. At point (3) the contact signature is missing one burst but the time and amplitude of the bursts has not changed substantially, indicating the contacts may not be the root cause of the problem. At the new point (4) we see a significant additional burst and it occurs on all taps but is more prominent and frequent at the higher tap positions than the lower positions. Again this change in the burst indicated drive shaft slippage as it is apparent the time taken for the completion of the contact movement has increased. Finally at point (5) the brake motor amplitude appears consistent with point (4) on Figure 7 but the there is again a time delay of approximately 0.5 seconds.

In all, it was decided that the transformer be taken out of service and an inspection of the tapchanger drive mechanism be made. The findings showed that slippage was indeed occurring in the key and keyway of the Geneva wheel. As quoted by the service technician "There was about 1 to 2 mm of play in the keyway which when taken to the extremities of the moving contacts equated to approximately 40mm of play. Considering that the distance between the fixed contacts is about 50mm, if the condition were left unchecked then a failure would have been inevitable." [(2)]

It is important to note here that to best see the changes in any signature there needs to be baseline data or footprints to compare with. Therefore, the footprints should be taken as soon as possible after delivery of a transformer or at the manufacturer's workshop during testing. It is recommended that 2 baseline signatures are stored. The first being in the de-energised state so that the data can be compared with before and after maintenance in the future. The second set of baseline data needs to be that of the unit in service under load conditions. This second set will be that used for comparison with the "normal" condition monitoring regime when undertaken.

The Future – Where to from here?

The work done to date has proven to be successful and yet the system is still in a prototype development stage. It has now been given additional funding by the Australian Strategic Technology Programme (ASTP), a research consortium managed through ESAA on behalf of nine Australian utilities. Ergon Energy has agreed to support the further development of the system by obtaining vibration signatures from a variety of tapchangers in both the workshop environment and in the field. The data will be collected before and after maintenance in Ergon's Virginia workshops. This data along with details of the actual physical findings will be used as a basis for providing eventual end users a sound database from which they can assess the condition of their plant.

To date, the data collected has been for one type of OLTC; a Fuller type bolt-on tapchanger and for this technology to be accepted by the wider community it will need typical vibration signatures from several other types and makes of OLTCs. As an indication of the variety of bolt-on tapchangers is service the ASTP did a survey of 7 Utilities and found approximately 38 different models from around 15 different manufacturers with some units as old as 50+ years. The different models numerous ranges and sizes within that model therefore giving over 250 of individual bolt-on tapchangers. The Ergon workshop refurbishes transformers and has access to the variety of tapchangers needed. As well, both Ergon and Energex have an extended range of tapchanger types in service so the field work can be carried out to confirm the typical base line data needed. During the field work any abnormal signatures would be investigated and the findings recorded against the signatures.

After collecting this data it is intended to produce a database that can act as a typical footprint for a particular tapchanger and thereby allowing users of the system to compare existing in-service tapchangers against that data. Over time end users would then gather sufficient data in house to continuously monitor their tapchangers for signs of wear or impending problems. As previously mentioned if signatures are taken at the time of initial testing in a manufacturer's workshop then as aging transformers are replaced the utility will, over time, have specific data on all its valued transformer assets. If the asset managers can prevent a fault on an average 15MVA 66/11kV transformer the savings could be: new transformer $250,000, remove old unit $50,000, temporary supply or load distribution costs $120,000, loss of revenue –unknown but large, investigation costs 25,000. Just from these approximate costs it is easy to ascertain that the savings gained would certainly outweigh the cost of monitoring.

The system has been developed around bolt-on style tapchangers and it would be remiss of the author not to mention the in-tank style tapchangers. Unfortunately these types of tapchangers are more difficult to access close to the location of the switching Powerlink Queensland funded an earlier research project by the QUT team to explore the possibility of obtaining vibration signatures from its Reinhausen type in-tank tapchangers. This exploratory study revealed both the possibilities and additional challenges and needs to be followed up with further work at an appropriate juncture. With the co-operation of transformer and tapchanger manufacturers it is surely possible to adapt the system to these units.

Further to the above the system will need to be developed into a commercially available product. In its present "prototype" form it is useful for initial gathering of baseline data but is not robust enough for the general market. It also has the potential to be combined with other condition monitoring devices to enhance the capabilities of some of the other asset monitoring systems available.

Conclusion

It can be seen from the information contained in this paper that the OLTC monitoring system will be a valuable tool for Asset Managers to use on their aging plant. Whilst it is still in a prototype development stage the results achieved have proven themselves by the prevention of catastrophic failures. The issue now is the gathering of sufficient data from the available range of OLTCs in service not only in Australia but world wide.

Once this type of data is readily available to asset managers the rate of failure of transformers due to the tapchanger will undoubtedly be reduced and therefore in our competitive environment, loss of supply to consumers will also be reduced.

Acknowledgements

The system described in this paper was developed by the Queensland University of Technology (QUT) with funding provided by the Queensland Electricity Transmission and Distribution (QETD). Energex provided funding and assistance for the evaluation phase of the initial work.

Thanks to the efforts of Dr. Pengju Kang and Associate Professor David Birtwhistle this project has provided successful initial outcomes that are now being further funded and progressed to ensure this technology can be utilised for prevention of tapchanger and transformer failures.

The author would like to thank Pengju and David for allowing some of the information and data they have gathered to be used in the preparation of this paper.

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12. The National Instruments LabVIEW is an industry software tool for designing test, measurement, and control systems.

Biography

Kerry Williams is Substation Standards Engineer – Transportable and Modular Systems at Ergon Energy in Brisbane. He has worked in the power industry since 1975 and has an extensive background in transformer manufacturing, refurbishment and maintenance for companies such as ABB and Areva. Kerry managed the Ergon Specialist Plant Services workshops in Brisbane from January 2004 until June 2005 and now works in the Ergon Energy Network Substation Maintenance and Standards group on special projects including this OLTC monitoring device, Mobile Substations and Zone Substation Standardisation.

Kerry graduated from the Queensland University of Technology (formerly QIT) in 1983.