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A High Voltage Switch Mode Assisted Linear Amplifier Based Voltage Source for Dielectric Low Frequency Domain Spectroscopy Measurements

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Abstract

This paper presents a Switch-Mode Assisted Linear Amplifier (SMALA) designed for use as a Frequency Domain Spectroscopy (FDS) excitation voltage source for the diagnostic testing of oil/paper insulation systems in large power transformers. The developed voltage source has a low output voltage noise level, low harmonic content and is capable of driving highly capacitive loads with a maximum output voltage of 800 Vp-p in the frequency range of DC to 100 Hz current limited to 20 mA. Disturbances in the output voltage associated with switching of the main switching amplifier are minimised through the control of the switching time, taking the slew rate of the correction amplifier into account. The switching time of the main switching amplifier can be effectively controlled using a combination of a simple RC filter on the output of the main switching amplifier and controlling the rise-time and fall-time of the MOSFET gate drive voltage. Using the developed SMALA unit, it was possible to perform FDS measurement on an oil/paper insulated transformer at elevated excitation voltage. This resulted in a non-linear response current manifesting as odd harmonics in the measured current.

1 Introduction

Unexpected failures of high voltage equipment, such as transformers, cables and switch gear, can cause major disruption to the power network, which will result in unscheduled outages, costs to customers and operators alike as well as the potential loss of life and property. Operating experience from numerous countries in the world has identified a constant trend in transformer failures over a number of years. This is despite large concerted efforts by numerous organizations to identify the root causes of failure and to correct said causes. The maintenance and monitoring programs, or lack thereof, have been cited as the root cause of many failures [1]. It is universally acknowledged, that an appropriate well planned maintenance, inspection and testing regime can significantly reduce the number and/or severity of the failures experienced. Condition based maintenance of power equipment is generally regarded as a more cost effective alternative to scheduled based maintenance techniques. Numerous techniques have been developed for estimating the condition of the paper and pressboard components in large power transformers. Frequency Domain Spectroscopy (FDS) is one of the major methods for determining the condition of the paper and pressboard insulation.

Conventional FDS methods are used to provide a measure of the dissipation factor $\tan(\delta)$ and complex capacitance $C^*(\omega)$ of the insulation system within a frequency band from $10^{-4}$ Hz to $10^3$ Hz [2]. Conventional FDS measurements are performed by injecting a sequence of discrete sinusoidal voltages at discrete frequencies, or by using a Chirp waveform, onto a de-energized transformer and measuring the resulting current. The primary winding, secondary winding and core/tank act as equipotential electrodes separated by the insulation system under test. The insulation system is modeled as a capacitor with associated loss and polarization/de-polarization effects.

A typical set-up for an FDS measurement on an un-energized transformer is shown in figure 1. This figure shows the measurement being performed on the insulation between the HV and the LV windings of a transformer [3].

![Figure 1: Typical experimental set-up for the measurement of the FDS response of the insulation between the HV and the LV windings of a transformer [3].](image)

In summary, the SMALA provides a voltage source suitable for FDS measurements on oil/paper insulated transformers, with the potential for improved diagnostic performance.
Conventional FDS measurements rely on the excitation voltage remaining low enough to avoid any non-linearity in the response of the insulation system under investigation, and yet high enough to achieve a good signal-to-noise ratio for the measured response current. Recent research has examined the possibility of using the non-linear response of the dielectric as a diagnostic tool for large power transformers [3]. To generate a non-linear response, the excitation voltage source must have a sufficiently large amplitude of at least 500 V_{peak}. Typically switching amplifiers; such as PWM driven class D amplifiers; would traditionally be used for such high voltage levels. However, the switching noise present in the output of these type of sources would be problematic when measuring the response current through a predominantly capacitive sample, as the high rate of change of the output voltage during the switching events would result in significant impulse noise on the measured response current. Further, very low harmonic content (i.e. very low distortion) is also required so that the non-linear current response is due only to the dielectric, and not the excitation source. Finally, the current sourcing capability of the excitation source is usually quite low for FDS applications, limited to approximately 20 mA. For these reasons, it was decided to investigate using Switch-Mode Assisted Linear Amplifier’s for this task.

A Switch-Mode Assisted Linear Amplifier is an amplifier which is a combination of a switch-mode or Class D switching amplifier, and a linear (Class A, AB, or B) amplifier [4, 5]. Linear amplifiers are commonly used for voltage test sources due to their excellent dynamic behavior and high fidelity. Switch mode amplifiers are however of low fidelity, but are able to contribute significant amounts of power and/or voltage to the output. By combining the two amplifier types together, a SMALA can gain the benefits of each amplifier type, being high voltage output and excellent dynamics [6]. Yundt’s paper [5] describes the switch mode component of the amplifier as the main amplifier and the linear portion as the correction amplifier. Four key configurations of the SMALA are possible, with the main and correction amplifier in either a series or parallel configuration, and the control variable being either a current or a voltage. For this FDS application, a series configuration is adopted; as a high output voltage is required with a relatively low output current; and voltage is selected as the control variable. The main amplifier can be a multi-level switching amplifier to achieve higher output voltages.

The operation of the series topology is showed schematically in figure 2. The main amplifier is used to provide a stepped voltage waveform $V_{m}$, which is close to the desired output voltage waveform $V_{o}$, whilst the correction amplifier produces a smaller voltage $V_{c}$ that is the difference between these two [7]. This configuration requires the DC supply to the correction amplifier to be sufficiently large enough to counter the voltage changes that occur in the main amplifier. A common method of implementing this series configuration topology is with a multilevel inverter of cascaded full bridge cells [6-8].

Three key modulation techniques are used for SMALA [7-9]. The first technique is pulse width modulation combined with an output filter to attenuate the harmonic components. As stated earlier, this would be unsuitable for use in FDS in a transformer condition monitoring application due to the generated noise. The second technique is nearest level control. This is a low switching frequency technique that monitors the input reference voltage, and compares this to a series of threshold voltages. As the reference voltage intercepts the threshold voltage, the next cell of the main amplifier is switched [8]. The correction amplifier stage in a nearest level control scheme is relatively complex. A much simpler control method is hysteresis control. This is used almost without exception in the parallel configuration [7], in which the current output from the correction amplifier is controlled to stay within preset hysteresis band limits. A voltage hysteresis control method can also be used to monitor the output of the correction amplifier in a series configuration, this is the approach used in this design.

2 SMALA amplifier design

A SMALA was designed and built to demonstrate its suitability for use as an excitation source for transformer condition monitoring via FDS. The developed amplifier is a three level series topology that uses voltage hysteresis control. The top-level schematic of the amplifier is shown in figure 3.

The main switching amplifier is in the form of an H-bridge comprising of switches $S_{11}$, $S_{12}$, $S_{13}$ and $S_{14}$ as well as a DC floating power sources $V_{sw}$. 500 V N-Chanel MOSFET’s are used as the switches. The isolated switching signals to these MOSFET switches are generated via a digital hysteresis control loop running on an ATMEL ATMega2560 microcontroller running at 16 MHz in the form of a state
machine. The input voltage to the control loop is derived from the output of the correction amplifier \( V_c \).

### 2.1 Correction amplifier

The correction amplifier is an in-house built class B push-pull MOSFET/BJT cascade shown in figure 4. The amplifier is an inverting configuration with the feedback path consisting of \( R_{fb} \) and \( R_{in} \).

Figure 4: Schematic of the high voltage correction amplifier.

The output stage of the correction amplifier is grounded, and amplifier output is instead taken from the mid-point of the floating high voltage split power supplies. This approach allows both the input and the output stage to be ground referenced. This greatly simplifies the drive of the output stages, and the power supply requirements of the voltage gain stages. Two conventional op-amps share the voltage gain of the correction amplifier. Capacitor \( C_1 \) on the first op-amp stage provides dominant pole compensation ensuring stability. Both op-amps are supplied by a conventional, grounded \( \pm 15 \) V dual supply. The correction amplifier with key components \( R_{in} = 10 \) k\( \Omega \), \( R_{fb} = 452 \) k\( \Omega \), \( R_1 = 100 \) k\( \Omega \), \( R_2 = 1 \) k\( \Omega \), \( R_3 = 1 \) k\( \Omega \), and \( C_1 = 167 \) nF, as indicated in figure 4 has a measured step response shown in figure 5. This shows the step response with the output at 386 V\(_{pp}\). The rise-time (0% to 100%) of the response is 288 \( \mu \)s. This gives a maximum slew rate of approximately 1.34 V/\( \mu \)s. Figure 6 shows the measured frequency response of the correction amplifier. From this figure, it can be seen that the closed loop DC gain of the correction amplifier is approximately 45.7:1 (33.1 dB) with a 3 dB corner frequency of approximately 1.8 kHz.

Figure 6: Correction amplifier measured frequency response.

### 2.2 Main switching amplifier

The slew rate of the correction amplifier is an important parameter, as this will determine the allowable switching times of the main switching amplifier. The switching time of the main amplifier need to be larger than the response time of the correction amplifier, as will allow the correction amplifier to compensate for any switching transients generated. Due to this, the switching times for the main switching amplifier should be no faster that approximately 2 ms to 3 ms at a 400 V\(_{pp}\) output. The main switching amplifier will use a MOSFET full H-bridge. The switching time of the bridge as a whole or the individual MOSFET’s will therefore need to be slowed down. Preliminary work done on this SMALA design used BJT’s as switching devices augmented with external Miller capacitance between the collector and the base of the transistor to slow the switching times of the transistors [10]. This technique was initially implemented in this design using MOSFET’s in place of BJT’s. This resulted in a design that was not robust due to intermittent failures of the MOSFET’s. This was traced to high-frequency switching noise being injected into the gates of the MOSFET’s via the added Miller capacitance. A more robust design involved slowing the rise-time and fall-time of the gate drive voltage as well as placing an RC filter on the output of the H-bridge as shown in figure 7 and 8.

An individual switch and driver is shown schematically in figure 7. The switching signal from the microcontroller \( V_{ON} \) is isolated from the MOSFET and its driver by an isolated data buffer. The supply voltage to the MOSFET driver chip is supplied via an isolated DC-to-DC converter. The rise-time and fall time of the switching voltage to the MOSFET gate can be controlled via \( VR_1/C_1/R_1 \) combination. Full control of the switching time of the main switching amplifier cannot be achieved reliably by only changing the rise-time and fall-time of the MOSFET gate drive voltage. An RC filter is additionally placed on the output of the H-bridge to assist with this. This is shown in figure 8. The output of the
switching amplifier $V_m$ is taken across the capacitor of the filter.

Figure 7: Isolated drivers of each switching unit of the switching amplifier.

Figure 8: Schematic of the main switching amplifier showing the output RC filter used to slow down the rise time of the output voltage.

3.2 Complete SMALA amplifier

Figure 10 shows the output of the SMALA at 720 V$_{p-p}$, with an input of 16 V$_{p-p}$ at 1 Hz. The overall SMALA amplifier has an inverting gain of 33.1 dB. Figure 10 also shows the output voltage of the correction amplifier as well as the main or switching amplifier. Figure 11 shows the switching points A and B in figure 10 in more detail. From this figure, it is seen that there is a small disturbance in the output voltage of the SMALA amplifier at the start of the switching event.

The output of the SMALA amplifier is required to have a very low harmonic distortion. This is due to the fact that the amplifier will be used to investigate any non-linearity’s present in the measured dielectric response of transformers, particularly at higher voltages. An analyses of the harmonic content of the output voltage shows that the Total Harmonic Distortion (THD) is measured to be 0.128% at an output level of 805.6 V$_{p-p}$.

Figure 10: The input and output of the correction amplifier for a 1 Hz sinusoid. The output voltage of the correction and switching amplifiers is also shown.

Figure 11: Switching points A and B in figure 10 in detail.
3 Dielectric response measurements

The designed SMALA amplifier was used to measure the dielectric response of a small oil filled 240 V/4 kV instrument transformer. Due to the relatively low voltage ratings of this transformer, a significantly large electric field could be generated between windings and between windings and earth and/or the electrostatic screen using the equipment available. The largest measured dielectric response signal was obtained when measuring from the low voltage winding to the electrostatic screen; all other windings as well as the tank were earthed to remove their effect from the results. The measurement set-up used is shown schematically in figure 12.

Figure 12: Schematic of the set-up used to measure the dielectric response of a 4 kV instrumentation transformer between the low voltage winding and the electrostatic screen. The resistor used to measure the response current $R_{\text{response}}$ is 100 kΩ.

The dielectric response of the transformer was measured at 0.1 Hz with excitation voltage $V_{\text{measure}}$ ranging from 40 V$_{\text{p-p}}$ up to 805 V$_{\text{p-p}}$. Figure 13 shows the measured dielectric response current $I_{\text{response}}$ as a result of the excitation voltage $V_{\text{measure}}$ at 805 V$_{\text{p-p}}$ at 0.1 Hz. From this, it is evident that there is a significant harmonic content in the measured response current due to the non-linear dielectric response at this particular frequency and excitation voltage level. There are small noise perturbations present in the response current at the points of SMALA switching. These are however relatively small and are tolerable in the present system and can be remove via post processing filtering. The harmonic content of the measured response current over a range of excitation voltage magnitude is shown in figure 14. From this, it is evident that the dielectric response predominantly contains odd harmonics. This has been reported in previous work [3] as the non-linearity is symmetric between the positive and negative halves of the excitation voltage. As the excitation voltage is increased, the THD of the measured response current increases, indicating larger amounts of non-linearity in the measured dielectric response as shown in [3].

Figure 13: Measured dielectric response current $I_{\text{response}}$ versus the excitation voltage $V_{\text{measure}}$ at 805 V$_{\text{p-p}}$ with a frequency of 0.1 Hz using the setup in figure 12.

Figure 14: Harmonic content of the measured response current $I_{\text{response}}$ measured at 0.1 Hz with excitation voltage $V_{\text{measure}}$ ranging from 40 V$_{\text{p-p}}$ up to 805 V$_{\text{p-p}}$.

4 Dielectric response processing

The dielectric of most insulation systems can be modelled as a resistor in parallel with a capacitor as shown in figure 15. When the dielectric response is non-linear, the resistor and capacitors value will be function of some parameter such as voltage, temperature, stress or strain etc. In these results, the dielectric response will be a function of excitation voltage and frequency only as temperature is kept constant. The dielectric can be modelled as shown in figure 15, where the resistor and capacitor values will depend on the exciting voltage. Using the measured excitation voltage, the fundamental and odd harmonics of the response current, it is possible to separate the response current into capacitive and resistive current.
components. The result of this separation is shown in figure 15 with an excitation voltage of 805 V$_{p-p}$ at 0.1 Hz for the response current measured showed in figure 13 after post processing to remove noise.

![Figure 16: Calculated current and charge versus excitation voltage from the data in figure 15.](image)

The calculated current and charge versus excitation voltage from the measured results in figure 13 is shown in figure 16. Figure 17 shows the calculated parallel capacitance and resistance for the sample using the fundamental voltage and current at 0.1 Hz. The resistance and capacitance versus excitation voltage can be used in diagnostic studies of the insulation condition in high voltage equipment. The measured parallel capacitance of the unit using an RLC bridge with an excitation voltage of 1 V$_{p}$ is 486 pF, while the calculated capacitance from the measurements is 480 pF. The calculated parallel resistance under the same conditions is 2.8 GΩ. A resistance value was not measured using an RLC bridge due to its extremely large value.

5 Conclusions

From this work, it is evident that a SMALA has the potential to be used in FDS measurements on predominantly capacitive samples. This is due to the produced excitation voltage being of high fertility and low noise. Disturbances in the output voltage associated with switching of the main switching amplifier can be minimised through the selection of the switching time, taking the slew rate of the correction amplifier into account. The switching time of the main switching amplifier can be effectively controlled using a combination of a simple RC filter on the output of the main switching amplifier and controlling the rise-time and fall-time of the MOSFET gate drive voltage.

Using the developed SMALA it was possible to perform FDS measurement on an oil/paper insulated transformer at elevated excitation voltage. This resulted in a non-linear response current manifesting as odd harmonics in the measured current. Using the fundamental results, it is possible to calculate the change in equivalent resistance and capacitance of the sample a function of excitation voltage.

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