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# Online monitoring of leakage current in AC motors

Preventing insulation resistance failure

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<p>The condition of winding insulation is a determining factor for the state of an entire AC electric motor. It can be monitored by utilising the relationship between winding insulation resistance and leakage current of the motor.</p> <p>The aims of this thesis were to present the methodology behind using leakage current to determine the condition of an electric motor, including the separation of resistive and capacitive leakage current. The study also includes an explanation of the Talas Leaker device from Talas Electric Oy. As the commissioner of this project, Talas Electric Oy's targets for this thesis were to have five working prototypes of the Talas Leaker and technical documentation prepared.</p> <p>The results of the study and subsequent experiments show the intrinsic properties of an electric motor's components (an increase in frequency with a constant voltage decreases leakage current, an increase in voltage with a constant frequency causes increases leakage current, absorption current effect of insulation resistance, the inversely proportional relationship between insulation resistance and capacitance of the windings and the proportional relationship between contamination of the windings and capacitance of the motor).</p> <p>The importance of such a device is vast and multidisciplinary; it can help prolong the life of electric motors and other electric equipment as well as prevent severe injury. Further study may be carried out to allow the Talas Leaker to separate between resistive and capacitive leakage, to measure two electric motors at once and to bypass the circuit board altogether.</p>	
Keywords	leakage current, winding insulation, electric motor, resistive leakage, capacitive leakage

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## Abbreviations

AC	Alternating current
CPU	Central processing unit
CT	Current Transformer
DC	Direct current
GPIO	General purpose input/output
HIPOT	High potential
k $\Omega$	Kiloohm
LCD	Liquid-crystal display
LED	Light Emitting Diode
mA	Milliampere
M $\Omega$	Megaohm
nF	Nanofarad
NEMA	US National Electrical Manufacturers Association
PCB	Printed circuit board
RCD	Residual-current device
STL	Stereolithography
V	Volts

## 1 Introduction

The degradation of winding insulation is one of the leading causes of motor failure worldwide; unsuitable environments, such as those with high temperatures, humidity and contaminants, aggravate the deterioration of the insulation, leading to premature breakdowns and reducing the operating life of the motor. [1,3] [2,1-2] [3,2]

By taking the correct measures to monitor the condition of the winding insulation, the working life of millions of motors and electric equipment could be extended and maintenance expenses could also be dramatically reduced. Fortunately, this can be achieved by utilising the relationship between winding insulation resistance and leakage current of an electric motor [2,3]. This solution allows the user to continuously monitor their electric motor, enabling them to schedule maintenance breaks while ensuring the staff are not exposed to unsafe levels of leakage current.

The purpose of this thesis is to present how leakage current can be used to monitor the condition of an AC electric motor and to detail the stages of development of a device, the Talas Leaker, which utilises this principle. The thesis was also carried out to determine the feasibility of such a device while preparing to bring the Talas Leaker to market. The Talas Leaker can continuously monitor leakage current of electric motors and display the data online, allowing the client to check the amount of leakage current at any time and receive alerts if the critical value is reached.

Talas Electric Oy is the commissioner of this project. They are a company focused on research, development and manufacturing; their goal is to provide solutions to their corporate clients' electrical device needs that will reduce energy consumption and maintenance expenses in the long-term. By carrying out this thesis, the benefit to the company is five prototypes of their product will be ready for sale by the end of the project. Unfortunately, as this thesis has a strong focus on the Talas Leaker, a patented product from Talas Electric Oy, some details may have to be omitted from the version published online due to confidentiality agreements.

## 2 Leakage Current

Leakage current is the natural phenomenon in electrical circuits of current flow from the circuit's live electrical components to the frame of the device or to ground. This is due to the intrinsic physics law that energy flows from higher to lower potential; when a conductor has a potential difference with respect to the earth (in other words, a voltage above 0 V), some current will flow from the conductor to the earth. Leakage current typically flows through the earth connection but may also flow through live or neutral wires. [4] [5,1]

Leakage currents can be found wherever electrical equipment is present, that is, in homes/offices, hospitals, power plants, factories and other industrial facilities that rely on electrical equipment. Although leakage currents are normally very small, they can still cause damage to electrical equipment and human health [6,1]. In an electric motor, the two causes of leakage current are resistive and capacitive leakage [4]. Together, they represent the total leakage current of a circuit or appliance, as shown in Equation 1:

$$i_t = i_r + i_c, \quad (1)$$

Where,  $i_t$  is the total leakage current,  $i_r$  is the resistive leakage current and  $i_c$  is the capacitive leakage current.

Capacitive leakage occurs due to the fundamental properties of capacitors (two conductive surfaces separated by a dielectric). When an alternating current is running between the conductive plates, some capacitance will develop between them, resulting in a leakage current. On the other hand, resistive leakage refers to the current loss through the insulation surrounding a conductor. Although advances in technology mean that very effective insulation has been developed, resistive leakage still occurs [7,1].

Capacitive and resistive leakage are dependent on the supplied voltage, with higher voltage increasing the leakage. Normally, there is more capacitive leakage than resistive leakage in a motor. However, only the amount of resistive leakage can give insight into insulation condition; an increase in resistive leakage in an AC electric motor suggests winding insulation resistance is in poor condition or has deteriorated. [8,1] [9,2]

Leakage currents in electrical circuits are undesirable and can be the cause of tripping, increases in voltage, electrocution, fires and noise. Typically, leakage current from an electric motor is very low (<1 mA) and has no negative impact or noticeable effects on the motor. [4] However, when the resistive leakage current reaches high levels for a period of time it signifies that the insulation and conductors of the motor have become hot and humid [2,5]; the motor may be close to failure. It is important that leakage current of an AC motor is continuously monitored so that maintenance personnel can be notified when levels are critical and action must be taken. It would also enable maintenance breaks to be scheduled in advance allowing the electric motor to be repaired before complete failure.

## 2.1 Leakage Current Clamp Meter

A clamp meter is a small handheld device used to measure the leakage current of a circuit. It is the most widely used, effective and non-intrusive method of leakage current monitoring as it allows leakage current to be measured without the need to disconnect or cut any wires. Measuring the leakage current of a device with a leakage current clamp meter is done in many commercial and industrial applications [12,1].

The working principle of a leakage current clamp meter is based on current transformers (CT) and electromagnetism; the reading on the clamp meter is dependent on the electromagnetic field strength the CT has detected when enclosed around the wire(s). The induction iron core allows the clamp to ignore magnetic fields outside the clamp, only monitoring the electromagnetic field produced inside it [12,1].

The disadvantages of leakage current clamp meters are their inability to continuously remotely monitor leakage current. Most devices have the functionality to store limited data internally as well as automatically power-off after a few minutes. This method of leakage current monitoring is ineffective as it would require someone to constantly supervise the device, transfer data to a computer and switch it back on at x-minute intervals.

The major advantages of these devices are that leakage current can be isolated without disconnecting the circuit and the clamp meter can measure individual wires in the circuit. Measurement is carried out by enclosing the clamp around the appropriate wiring; from experience in this project, the most accurate and stable results occur when the wire is perpendicular to the clamp, not touching the clamp jaws. Different measurement scenarios depending on the type of circuit and intended measurement can be found in section 2.2.

Please note, the difference between a leakage clamp and a residual-current device (RCD) is that an RCD does not measure anything, but rather, just breaks a circuit when it detects that the current in the neutral and phase wires is not equal. The purpose of an RCD is to protect people from electric shock.

## 2.2 Measurement

Leakage current measurement can be carried out on single and three-phase circuits. To measure the combined leakage current of the circuit wiring and of the load, the measurement must be made with the load connected, that is, by turning on the electric motor or other appliance. To only measure the leakage current of the circuit wiring, the load must be disconnected, that is, by turning off the electric motor or other appliance [4].

In theory, if measuring multiple live conductors simultaneously (for example in a three-phase circuit), the magnetic fields generated by their load currents should neutralise each other. However, in reality, electric circuits are not perfect and the clamp meter will show a reading corresponding to the magnetic field being produced by leakage current from the live conductors to ground [4]. To measure the leakage current flowing to ground (in other words, the leakage current of the electric device) in a single-phase circuit, the live and neutral conductor must be measured together (Figure 2).

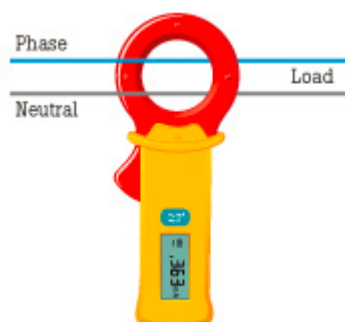


Figure 2. Leakage current to ground of a single-phase circuit, reprinted from Fluke.com (2018) [4]

To measure the leakage current flowing to ground in a three-phase circuit, all three phase conductors, as well as neutral (if present, for example, in a three phase four wire circuit), must be measured together (Figure 3).



Figure 3. Leakage current to ground of a three-phase circuit, reprinted from Fluke.com (2018) [4]

Another technique to measure the leakage current flowing to ground is to only clamp the ground connection (Figure 4). The technique shown in Figure 4 does not measure the complete leakage current of the entire circuit.

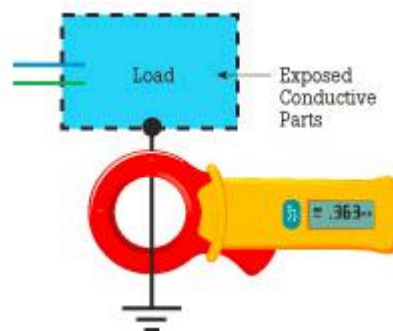


Figure 4. Leakage to ground through ground connection, reprinted from Fluke.com (2018) [4]

Unfortunately, the majority of monitoring techniques on the market today are very complex, expensive, unable to continuously monitor leakage current or cannot be supervised remotely. Maintenance staff must manually measure the leakage current at given time intervals, which is not only ineffective but also increases the likelihood of human error or injury.

The GLC-9000 (Figure 5) is a complex device, which can measure the leakage current of medical and general purpose electronic equipment. It has four leakage current measurement modes, nine measurement networks and numerous other features [13]. However, the disadvantages of this device are that it has no online capabilities and its intricate features increase its value, making it unaffordable to most potential clients.



Figure 5. Instek GLC-9000 Leakage Current Tester, reprinted from Gwinstek.com (2018) [13]

Similarly, the ST5540 (Figure 6) is a leakage current measurement device for medical-use electrical devices and other electrical equipment without online capabilities. The ST5540 has a number of measurement networks capable of simulating a human body and other complex features [14]. Although these capabilities are desirable in niche sectors, most clients relying on electric motors for daily operations would find them unnecessary. Instead, the main requirement of a leakage current monitoring device is simply the ability to remotely monitor leakage current.



Figure 6. The Hioki Leak Current HiTESTER ST5540, reprinted from Hioki.com (2017) [14]

Texas Instruments have also created Leakage Current Measurement Reference Design for Determining Insulation Resistance, an assembled board able to monitor insulation resistance up to 100 M $\Omega$  with a 500 V DC power supply (Figure 7). It works by measuring the leakage current to determine the condition of insulation resistance. However, this product is made for testing purposes only and is not available for sale. [15,1]

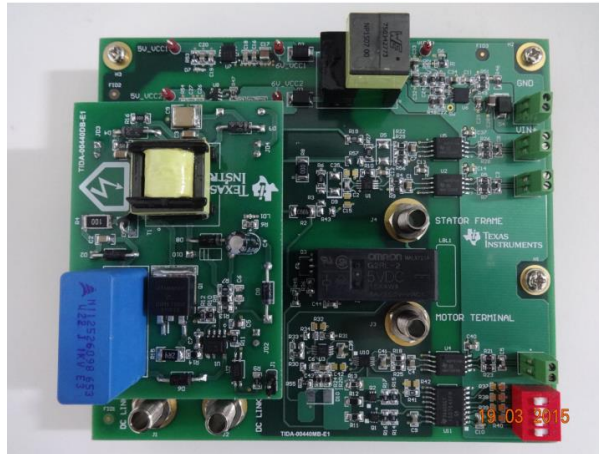


Figure 7. Leakage Current Measurement Reference Design for Determining Insulation Resistance from Texas Instruments, reprinted from *TI Designs* (2015) [15,1]

Talas Electric Oy also has a device, the Talas Measurer, which measures insulation resistance. However, like the Instek, Hioki and Texas Instruments devices, it can only measure when the motor is not under voltage (in other words, when the motor is not running). The issue with this method of insulation resistance monitoring is that since many motors are running continuously, perhaps stopping one day per year, the measurement can only occur once annually. The insulation resistance quality, temperature, humidity and other environmental factors fluctuate constantly throughout the year, making this method inaccurate and ineffective. Therefore, a simple device able to continuously and remotely monitor leakage current can be revolutionary in today's electrical motor market by extending the working life of millions of electric motors worldwide.

### 2.3 Previous Studies

Over the years, there have been many studies from researchers in the electrical engineering field with a focus on insulation resistance and leakage current. This chapter will present studies, which have provided innovative claims.

#### 2.3.1 Hipot Testing

Davis, the author of the article 'Real vs. total current ac hipot testing determines true insulation quality', demonstrates that the capacitive and leakage current must be separated in order to accurately gauge the condition of insulation [5,4] [8,1] [9,1-2]. This statement has been reiterated numerous times by several authors, so much so that it has become a generally accepted fact in the electrical engineering field. Visualisations of capacitive and resistive leakage current can be seen in Figure 7.

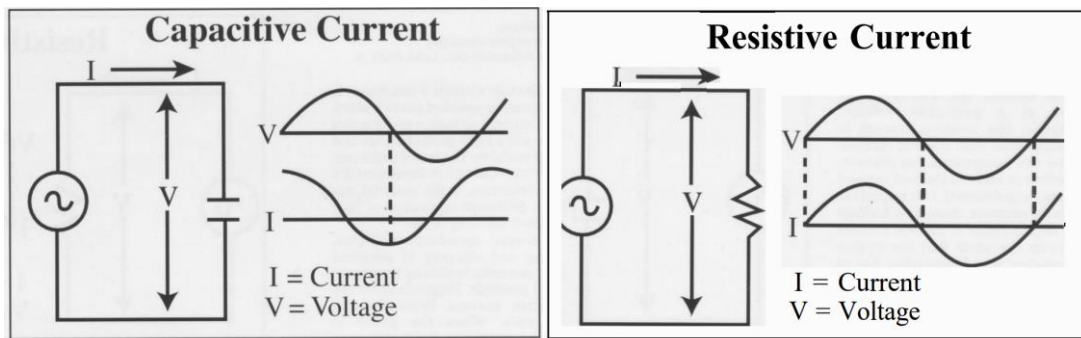


Figure 8. Left: AC test voltage over a capacitor. Right: AC test voltage over a resistor. Reprinted from Davis (1998) [9,1-2]

An AC test voltage over a capacitor creates reactive current 90 degrees out of phase with the voltage (left) whereas an AC test voltage over a resistor creates leakage current in phase with the voltage (right) (Figure 8) [9,2].

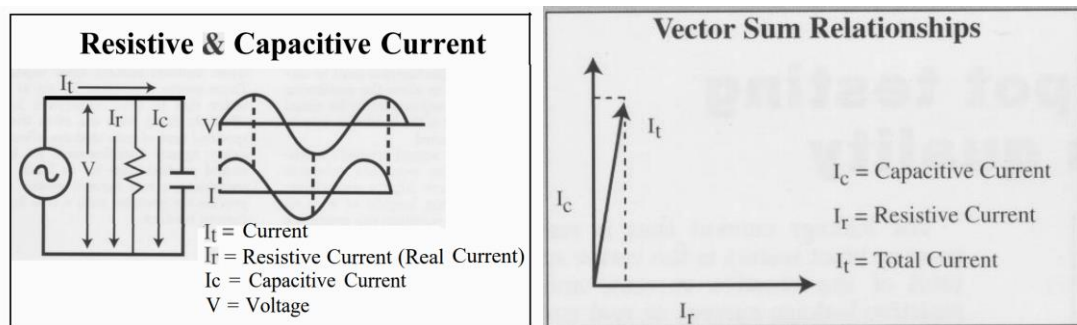


Figure 9. Left: Total leakage current. Right: Vector sum of resistive and capacitive leakage currents. Reprinted from Davis (1998) [9,1-2]

As reactive current (capacitive) is usually many times larger than the real current (resistive), a sudden spike in the real current may not be seen; this can be avoided by separating the currents. This phenomenon is visualised in Figure 9: using Kirchhoff's Current Law, the total leakage current is the sum of the resistive and capacitive current (left), the resistive current vector is along the x-axis, the capacitive current vector is along the y-axis and the vector sum is represented by  $I_t$  (right). The leakage current measured will be the sum of the currents,  $I_t$ , which is not a good representation of the ratio of resistive to capacitive leakage current present. The article also indicates that, according to NEMA, the definition of dielectric failure is the real resistive leakage current being over 10 mA [9,2].

The Talas Leaker device does not distinguish between capacitive and resistive leakage current, but instead measures the total leakage current to ground; the feature must be added in the future for more accurate measurement of changes in resistive leakage.

### 2.3.2 Composite Insulators and Electrical Devices

Amin, Amin and Ali [5,6] outline leakage current measurement techniques and their viabilities in certain applications. A HIPOT test or Dielectric Withstand Test is a popular method of testing insulation condition in which extremely high-voltage (>1500 V on equipment intended for 220 V) is applied to the insulation for a short period of time and the leakage current to ground is measured. 'If the insulation of product can withstand a much higher voltage for a given time then it can withstand normal voltage for its whole life.' [5,6].

Amin, Amin and Ali [5,4-5] explain that leakage current caused by insulation deterioration is unrelated to capacitance although the majority of leakage current is capacitive, a statement harmonized by Davis [9,1-2] as discussed in section 2.3.1. Regardless, only resistive leakage current is considered when analysing the condition on an insulator; this is due to the fact that capacitance is constant as the power frequency everywhere is 60 Hz. The maximum leakage current for consumer and medical devices should be 100 mA, although not implemented by any organization standard as the maximum is unique to every situation [5,4-5].

Commonly stated in the field, Amin, Amin and Ali's study [5, 5-6] expresses that the amount of leakage current is dependent on the environmental conditions; in a cool, dry area, leakage currents are normally less than 5 mA whereas in wet conditions, leakage currents may increase by 50 mA and remain safe. A sudden rise in leakage current followed by a steady decrease over the next few hours does not signify something is wrong but rather, that an increase in the humidity near the insulators occurred. If the high leakage current value does not decrease over time then maintenance is required. [5,5-6]

Amin, Amin and Ali's study [5,9] emphasises how pollution on an insulator's surface affects the insulator's hydrophobicity and leakage current; thus, these are the properties commonly used to determine the condition of the insulator. Leakage current measurements have an advantage over hydrophobicity measurements: human involvement near the insulation is not necessary for leakage current measurement, making it the safer, more practical solution used worldwide for condition monitoring. Leakage current is directly proportional to surface pollution deposit; in other words, the more surface deposit, the more leakage. As water becomes trapped under a layer of pollution, the surface resistance of the insulator decreases. Their relationship can be modelled by Equation 2 [5,9]:

$$S = \pi(r_2^2 - r_1^2). \quad (2)$$

Where  $S$  is the area of the pollution layer,  $r_1$  is the radius of the insulator and  $r_2$  is the combined radius of the insulator and pollution layer.

More simply, Equation 2 uses the equation for calculating the area of a circle,  $\pi r^2$ , (in this case, the circle is the cross-section of a wire) to determine the combined cross-sectional area of the wire and pollution layer, then subtracting the cross-sectional area of the wire. Additional relations as stated in Amin, Amin and Ali's study [5,11-12] are listed below:

1. Hydrophobicity is directly proportional to leakage current.
2. Humidity is directly proportional to leakage current.
3. UV radiation decreases leakage current on composite and ceramic surfaces.
4. Increasing the minimum distance along the surface between two conductive parts (creepage) of a ceramic or composite insulator decreases leakage current.
5. The temperature of the surroundings does not affect leakage current significantly. [5,11-12]

Amin, Amin and Ali [5,13] reiterate that leakage currents to ground of electrical devices are a safety risk and the sole cause is deterioration of insulation. Humid, wet and polluted/salty conditions are the main causes of insulation weakness and hence, leakage current. The authors claim that in numerous cases, the leakage currents measured in the field are lower than those measured during aging tests in a laboratory, proposing that the time between maintenance breaks can be longer than those predicted during testing. [5,13]

### 2.3.3 Modified Shifted Current Method

Shaha, Thosar and Moroney [16,1] state that the negative consequences on an electrical device of capacitive leakage current are smaller than those of resistive leakage current, a statement in line with Davis [9,1-2] and Amin, Amin and Ali [5,4-5]. They offer measurement techniques for isolating the resistive leakage current of a surge arrester by extracting it from the total leakage current after subtracting the capacitive part. The resistive leakage can then be used to establish the condition of an electrical device: as it increases, the lifetime of the surge arrester decreases. Their method for the extraction of resistive leakage current is called Modified Shifted Current Method; this method does not require an applied voltage. [16,1]

Other methods described include the Compensation Method, Variable Coefficient Compensation, Multi-coefficient Compensation and Probe Current Method. A limitation of this study, as stated by the authors, is that leakage current measurement using a current transformer, such as a leakage current clamp meter, is not possible for online application. [16,2-3]

The techniques described in Shaha, Thosar and Moroney's study provide a great opportunity for further studies and could possibly be applied to the Talas Leaker to enable it to separate the resistive part of leakage current.

### 2.3.4 IEC950 Safety Standard

The IEC950 safety standard specifies the maximum leakage current values that are considered safe for consumer and medical devices. Class II equipment (double insulated electrical appliances, which do not require a connection between chassis and electrical earth) may produce a maximum of 0.25 mA. Class I equipment (appliances that have their chassis connected to electrical earth) may produce from 0.75 mA to 5% of the total input current [17,5].

### 3 Methodology

The information in this section has been omitted due to confidentiality agreements.

## 4 Results

### 4.1 Talas Leaker Prototypes

One of the objectives of this thesis was to produce five working Talas Leaker prototypes; this goal was met by the end of the project. Table 4 details the specifications of the prototypes and some basic measurements:

*Table 4. Prototype specifications*

Device no.	Code	Accuracy	1 (mA)	2 (mA)	3 (mA)	Note
1	No code	$\mu\text{A}$				Testing
2	TL-0001MCA	$\mu\text{A}$	0.0029	0.214	0.210	
3	TL-0002MCA	$\mu\text{A}$	0.0058	0.227	0.203	RJ45
4	TL-0001MA	mA	0.1	1.8	1.5	
5	TL-0002MA	mA	0.0	1.7	1.5	RJ45

Table 4 outlines the product codes of the five Talas Leaker prototypes and leakage current measurements when the clamp was not connected (1), measuring a laptop power cord (2) and measuring the power cord of the Talas Leaker itself (3). The measurements were taken by clamping the neutral, phase and ground wires. As discussed in section 2.2, this is not a proper procedure for accurate leakage current readings. However, the aim was to see large enough differences between the currents detected by the devices rather than detect the actual leakage current.

The first prototype has no product code and no initial readings as it was immediately taken to be tested at Nor-Maali paint factory in Russia after assembly. Devices 1-3 have a range of 0.000 mA - 60.00 A and a resolution of 1  $\mu\text{A}$  while the devices 4-5 have a range of 0.0 mA – 600 A and a resolution of 1 mA. Talas Leakers TL-0002MCA and TL-0002MA have extra RJ45 socket holes on the bottom from the original design.

The RJ45 holes were closed using rubber covers. As can be seen from measurement 1, three of the tested Talas Leakers do not start measurements at 0.000 mA but this can be solved by updating the code to subtract this initial value or by calibrating the devices. Although the readings of similar devices are very close, devices 1-3 give very different readings to 4-5 as they are using different internal components. This is most likely due to a software issue as the code was originally written for the components of devices 1-3. The order the devices were built is as follows: 'No code', TL-0002MCA, TL-0002MA, TL-0002MCA, TL-0001MA.

## 4.2 Testing

Prior to building the Talas Leaker, some experiments were performed in order to observe the relationships between insulation resistance, capacitance and leakage current. These experiments were carried out at Talas Electric Oy's workshop in Sipoo where suitable equipment is located, including an electric board, an AC motor and an adjustable power supply.

Once the Talas Leaker prototypes had been assembled, the next steps involved testing them to ensure they worked properly. Testing was done in the Talas Electric office with a desktop computer and using the power cord of an adjustable table top fan.

### 4.2.1 Leakage Current and Capacitance Discharge Calculator

To understand how leakage current responds to changes in the condition of winding insulation in an AC motor, tests were carried out at Talas Electric Oy's workshop. Firstly, Talas' 'Leakage Current and Capacitance Discharge Calculator for X caps and Y caps' was used to calculate the leakage current from line to ground (Figure 24). This calculator is used to predict how an AC line filter will operate during a safety test. X capacitance refers to the capacitance discharge of the filter and Y capacitance relates to leakage current. The following inputs were used for the calculation:

$$\begin{aligned}
 C_X &= 10 \mu F \\
 C_Y &= 4.6 \text{ nF} \\
 R_{shunt} &= 10,000 \text{ k}\Omega \\
 V_{mains} &= 400 \text{ V rms} \\
 f_{mains} &= 50 \text{ Hz} \\
 I_{leakage} &= \frac{V_{mains}}{10^5}, \\
 &= \frac{400 \text{ V rms}}{10^5}, \\
 &= \frac{400 \text{ V rms}}{2 \cdot \pi \cdot 4.6 \text{ nF} \cdot 50 \text{ Hz}} \\
 &= 0.5781 \text{ mA} \approx \mathbf{0.6 \text{ mA}}.
 \end{aligned}$$

According to these calculations, the leakage current measured from the testing setup should be approximately 0.6 mA.

Total nominal X capacitance:	10	uF	Use 10 M Ohms if there is no shunt resistance (probe resistance).
Total nominal shunt resistance:	10000	kOhms	
Nominal, one branch, Y capacitance:	4.6	nF	
Mains voltage (worst case):	400	V rms	
Mains frequency (worst case):	50	Hz	

With these values the results of your safety tests will look approximately like those shown below.

Leakage current from line to ground:	0.5781	mA	Common limits are .75mA for ungrounded equipment, and 3.5mA for grounded equipment.
Time constant of capacitance discharge:	100.000	s	Normally, the voltage across the plug pins must be less than one second after being disconnected from the supply. Industrial twist lock connectors must comply with the same limit, but ten seconds after disconnection from their supply.
Peak voltage across pins after one second:	560.06	V peak	
Voltage across pins after ten seconds:	511.85	V peak	

Figure 24. 'Leakage Current and Capacitance Discharge Calculator for X caps and Y caps' used by Talas Electric Oy

Figure 24 shows a screenshot of the calculator and the inputs to get the result of leakage current from line to ground.

#### 4.2.2 Voltage and Frequency

The second experiment carried out consisted of changing the frequency and voltage supplied to the motor with the intention of demonstrating how these variables affect the leakage current. The frequency and voltage were regulated using an adjustable power source to supply power to the motor. In principle, voltage and frequency are completely unrelated. Voltage is the electric potential between two points whereas frequency is the rate at which current changes direction per second. Although not related by any equation, voltage *with* frequency, otherwise known as AC voltage, is common (voltage *without* frequency is known as DC voltage). Using an example, when the voltage is 100 V AC and the frequency is 50 Hz, it means the voltage will follow the sine wave pattern (0 V – 100 V – 0 V – -100V – 0) fifty times per second (Figure 25).

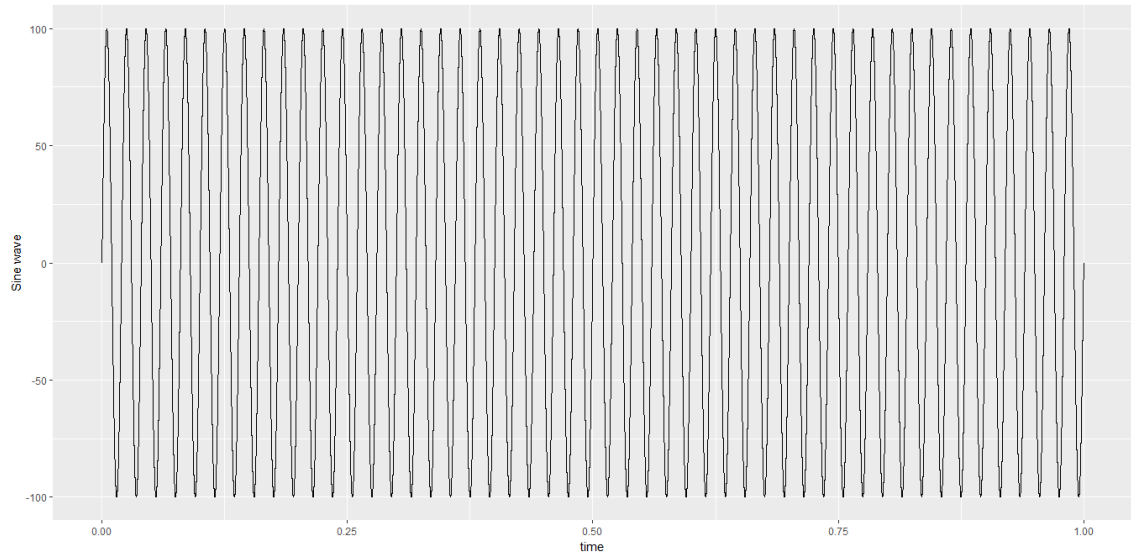


Figure 25. Sine wave of 100 V AC 50 Hz current

The graph (Figure 25) displays fifty repetitions of the sine wave over one second, with a maximum of 100 V and minimum of -100 V (graph made with MATLAB). Leakage current varies based on the applied voltage and frequency. Table 5 displays the measurements from a leakage clamp meter of the leakage current in mA when a constant voltage of 300 V was applied and frequency was changed.

Table 5. Leakage current at varying frequency and constant voltage

Voltage (V)	Frequency (Hz)	Leakage current (mA)
300	45	0.38
300	50	0.25
300	55	0.20

When the frequency is increased and the voltage is kept constant, the leakage current decreases (Table 5). This is due to the capacitive reactance of the system, which decreases as the frequency of the power supply increases. Theoretically, capacitive reactance will reduce voltage more than current, but in this case, the voltage is kept constant by the variable power source; therefore, only the current is reduced. The resulting decrease in leakage current is due to the total current reduction of the system. [19] However, the opposite occurs when the frequency is kept constant and the voltage is increased (Table 6).

Table 6. Leakage current at varying voltage and constant frequency

Frequency (Hz)	Voltage (V)	Leakage current (mA)
50	100	0.07
50	300	0.25
50	305	0.27

Thus, increasing voltage and having constant frequency causes the leakage current to increase (Table 6). This is consistent with the theoretical background that an increase in voltage causes an increase in leakage current [8,1] [9,2].

#### 4.2.3 Insulation Resistance

Capacitors are normally found in motors as start or run capacitors. They are used to alternate electric current from one winding to another in a single-phase AC induction motor in order to generate a rotating magnetic field [20]. The initial insulation resistance of the motor being tested was 2,000 M $\Omega$  and capacitance was 4.6 nF. After steaming the insulation, the motor's insulation resistance was 1.3 M $\Omega$  and capacitance was 6 nF. The insulation resistance was measured again once the leakage current had been found; in this short time, it had already risen to 4 M $\Omega$ . The windings were then steamed a second time and had an insulation resistance of 1.03 M $\Omega$  and a capacitance of 10.26 nF. After taking the third measurements, the insulation resistance had dropped to 600 k $\Omega$ . These results can be seen in Table 7 (results to two decimal places).

*Table 7. Insulation resistance and capacitance of the motor windings*

Steam	Insulation Resistance (M $\Omega$ )	Re-	Capacitance (nF)	Insulation Resistance after measurements (M $\Omega$ )
Initial	2,000.00		4.60	
First steam	1.30		6.00	4.00
Second steam	1.03		10.30	0.60

The insulation resistance rises quickly during the first few minutes (approximately five minutes) after the insulation was damaged with steam (Table 7). This is to be expected; if the insulation of the motor is in good condition, its resistance will continuously rise during the time (five to ten minutes) immediately after being damaged due to the absorption current effect; it can be concluded that the winding insulation in this case was in good condition [2,5].

A trend is shown between the insulation resistance and the capacitance: the lower the insulation resistance, the higher the capacitance of the windings (Table 7). It is already known that insulation resistance decreases as contamination on the windings increases [2,1-2]. Consequently, the capacitance also increases due to a capacitor's main principle; in a motor, a capacitor is created between the windings, stator core/motor casing iron (conductive plates) and insulation (dielectric) [3,5-6]. Pollution starts to attach to the stator core and motor casing iron, causing it to increase in size and thus to have a larger surface area (Figure 26).

The relationship between these variables is shown with Equation 3 below:

$$C = \frac{\epsilon \cdot A}{d} \quad (3)$$

Where  $C$  is the capacitance in farads,  $\epsilon$  is the permittivity of the dielectric,  $A$  is the area of plate overlap in metres squared ( $m^2$ ) and  $d$  is the distance between plates in metres (m).

Equation 3 can be visualised using Figure 26, where  $d$  (the distance between plates in metres) is represented by the insulation in red.

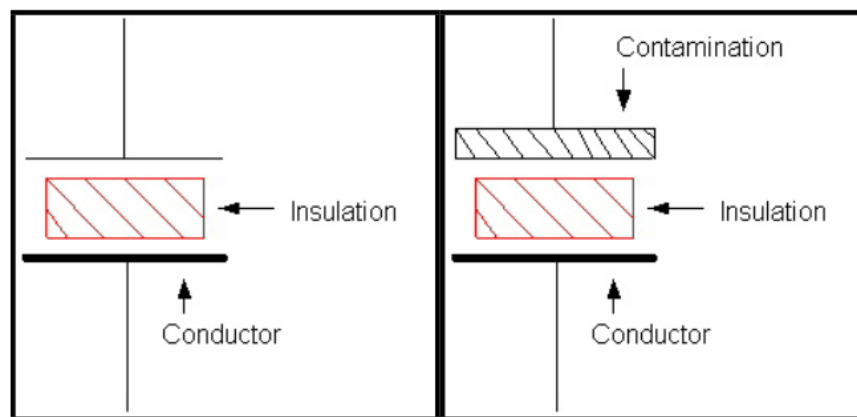


Figure 26. Contamination on conductor surface, reprinted from Bethel (2018) [21]

From Equation 3 above, it can be seen that if the permittivity and distance between the plates (insulation, Figure 26) are kept constant but the area of one of the conducting surfaces increases (contamination, Figure 26), the capacitance must increase. As particles and contamination agglomerate on the conductor, its surface area increases. Therefore, the more contamination on the winding, the higher the capacitance of the motor [3,5-6]. The leakage current in milliamperes of the non-operational and operational motor was also measured in different locations after steaming windings (Table 8).

Table 8. Leakage current of non-operational and operational motor after steaming

Leakage current (mA)		Ground wire at board	Main feed cable at compressor	Separate wire to ground
Non-operating	1	11	0.1	0.03
	2	0.17	0.05	
	3			
Operating	1	5.45	1.85	15
	2	11	1.64	13
	3	10.1		

Table 8 illustrates the leakage current in milliamperes: during the initial measurement (1), once the windings were steamed once (2) and once the windings were steamed a second time (3).

#### 4.2.4 Office Testing Environment

The information in this section has been omitted due to confidentiality agreements.

#### 4.3 Documentation

Documentation to accompany the Talas Leaker for the purpose of bringing it to market were also a requirement of this project; samples of the actual documents can be found in Appendices 1-10.

Assembly and code installation instructions (Appendix 1) are in-depth instructions for employees responsible for the assembly of the Talas Leaker. Component and wire references are in accordance with the numbering on the component and wire specifications. The work schematic (Appendix 2) can be used by employees as a guideline for the assembly of the Talas Leaker; it is different from a technical schematic as pictures of the components are used rather than sketches to make identification and construction simpler. The numbering on the connection lines corresponds to the wire numbers on the wire specification.

The component specification (Appendix 3) includes all components used for the assembly of the Talas Leaker. The respective component codes, technical information, prices and links are given. The total cost of building the device is also calculated. A Talas Leaker 3D model and drawing (Appendix 4) shows the model and drawing displaying the external DIN rails and all holes that must be drilled in the frame, their dimensions and measurements. The 3D model and drawing were created using Solidworks 2016 Student Edition.

A Solidworks drawing of the handheld leakage clamp designed can be found in Appendix 5. The internal wire specification (Appendix 6) includes technical information about the internal wires of the Talas Leaker. The wire types, lengths and endings are specified. The wire numbers correspond to the numbering as shown in the work schematic. Links are also provided in the specification but prices are not given as the lengths are so small relative to the wire roll sold in stores that their values are very low.

The external cable specification (work) of the Talas Leaker is intended for employees who are working to assemble the device and its external cables. The specification includes information about the external plugs, cables and wire/pin number configuration as well as information regarding the sockets of the device and the wires attached to them. Similarly, the external cable specification (client) includes relevant information for the client, in other words, external sockets, plugs and corresponding wire connections. These documents can be found in Appendix 7. The technical schematic (Appendix 8) shows the exact pins used for connection and the schematics of several components. The drawing is made with PADS.

A Talas Leaker socket hole drawing (Appendix 9) shows the socket hole drawing, dimensions and placements of the bottom holes on the Talas Leaker. The 'Getting started' product card (Appendix 10) provides the client with basic information on the functions of the bottom panel of the Talas Leaker as well as rudimentary facts about the device.

## 5 Discussion

The benefits of a leakage current monitoring system, such as the Talas Leaker, are numerous and multidisciplinary. As discussed in previous sections, the ability to monitor the leakage current in the context of AC motors gives the user insight into the condition of their motor's insulation resistance, which in turn can be used to estimate its life expectancy. In itself, this leakage current monitoring device is advantageous across many fields, for example, in power plants, pulp and paper mills, sewage treatment plants and applications requiring fans, pumps, compressed air etc, where motors and other devices are powered on continuously. For motors and other devices that can be switched off at regular intervals, automatic offline measurement is more accurate.

Various other professional fields and disciplines could benefit from the Talas Leaker, for example, the medical sector, the food industry and any other industry relying on electric devices. Despite the broad applications of the device, there are mutual advantages for all; the device extends the operating life of an appliance and prevents life-threatening injuries or fatalities while reducing environmental impact and expenses.

In the medical sector, a continuous leakage current monitoring device is necessary for ensuring patient safety when attached to a medical instrument; a high leakage current flowing to ground through a human can be fatal. In fact, even a small amount of leakage current can be deadly to a human, especially so to a patient who is already weakened by illness (Figure 29).

<b>mA</b>	<b>Effect on Human Body</b>
0.5 - 3	Tingling sensations
3 - 10	Muscle contractions and pain
10 - 40	"Let-go" threshold
30 - 75	Respiratory paralysis
100 - 200	Ventricular fibrillation
200 - 500	Heart clamps tight
1500 +	Tissue and Organs start to burn

Figure 29. Effect of current on human body, reprinted from Tiwari (2017) [23]

Figure 29 shows the effects of AC current of 60 Hz frequency on the human body. In hospitals, often patients are connected to electrical equipment that aid in their recovery. If the medical instrument is connected to a power supply and its frame is connected to the patient, a small amount of leakage current will flow through the patient. The amount of leakage current that flows through the patient rather than through the ground connection is indirectly proportional to the resistance of the patient; that is, the more resistance the patient has, the less current will flow through them as current always chooses the path of least resistance. [7,2] An example calculation can be shown below:

$$\begin{aligned}
 I_{leakage} &= 200 \mu A, \\
 R_{patient} &= 1,000 \Omega, \\
 R_{instrument} &= 1 \Omega, \\
 \frac{I_{patient}}{200 \mu A} &= \frac{1 \Omega}{1,000 \Omega}, \\
 I_{patient} &= 200 \mu A \times \frac{1 \Omega}{1,000 \Omega} = \mathbf{0.2 \mu A}.
 \end{aligned}$$

Hence, if the leakage current in a medical device is 200  $\mu A$ , its resistance is 1  $\Omega$  and the resistance of the patient is 1,000  $\Omega$ , the patient will only receive 0.2  $\mu A$  of current which, according to Figure 29, is negligible or may cause tingling sensations. However, if the ground connection becomes compromised, the patient will receive 200  $\mu A$  of current, severely affecting their heart. Depending on the patient's condition, this amount of current may be deadly. [7,2]

### 5.1 Future developments

The options for future development of the Talas Leaker are vast; however, two modifications to the current prototype are feasible in the short-term. The first modification is to connect two leakage clamps to one device; this would allow the user to monitor two electric motors (or some other appliance) with one Talas Leaker. This can be accomplished by installing a second audio jack socket in the frame and adding an internal relay, that can switch between readings from one clamp (motor A) to the other (motor B) after a specified amount of time. Further testing is required to understand exactly how the audio jack sockets and components could be connected.

The second modification is to convert the entire Talas Leaker device to one single electronic board, a solution requiring in-depth research, electronics engineering and testing. Nevertheless, this idea would significantly reduce the cost and size of the Talas Leaker. All modification scenarios require further research and testing, as well as changes to the code of the Talas Leaker; unfortunately, this is beyond the scope of this thesis.

## 5.2 Limitations and Possible Sources of Error

During the course of this thesis, several issues arose which negatively impacted its outcome. The first was concerning the code of the Talas Leaker. The personnel at Talas Electric Oy had already started work on the Talas Leaker in 2016 however due to a shortage of employees, the device could not be continued until October 2017, the start of this thesis. During 2016, the code for the Talas Leaker was written and installed on an SD card. Due to handling errors, the SD card was misplaced. Luckily, the SD card was located but approximately one week was spent trying to find a solution to the missing code.

Another issue that arose was the matter of which software to use for the correct formatting of schematics. Talas Electric Oy uses Microsoft PowerPoint for the work schematic and AutoCAD Electrical for the technical schematic. However, for my personal aims for this thesis, AutoCAD Electrical did not have the features and overall appearance I wanted. I tried using software including Eagle, KiCad and Fritzing, but could not make the document as some feature was always missing (in most cases, the ability to make a customised component). In the end, I found the best software for designing the final technical schematic, PADS.

Some limitations of this project were:

- Missing data – Tables 7 and 8 showing the leakage current, insulation resistance and capacitance of the electric motor in certain situations contain a number of missing values, as indicated by the empty cells. This occurred due to a lack of communication and organisation before the experiments were carried out in Sipoo. In the future, measurements should be made systematically.

- Data chosen at random – another consequence of the spontaneity of this experimentation and lack of planning is that the values used during the experiments were randomly chosen, (Tables 5 and 6). In Table 5, the frequency increases in intervals of 5 Hz whereas in Table 6, voltage increases by 200 V and then by 5 V. The inconsistencies in the intervals compromise the validity of the results.
- Missing photos – I was not able to get a photograph of the handheld leakage clamp that I designed before it was taken away to be tested with the first prototype at Nor-Maali paint factory in Russia.
- No test data - Nor-Maali were supposed to install the Talas Leaker prototype as soon as they had received the device (around November 2017) to accumulate test data by January 2018 but they still have not done so.
- No chance to test Talas Leaker in the workshop – this occurred due to lack of time and resources; I was unable to get to the workshop by myself using public transportation as it is in a remote location.

Many of these limitations are due to a lack of planning and communication. If I were to do the project again, these are the aspects I would focus on and change.

### 5.3 Development and Reflection

For this thesis, I had my own personal goals that were achieved: I gained an in-depth knowledge of leakage current properties and advanced technical and practical skills necessary for the assembly of electronic devices and subsequently, making the required technical documentation. Most importantly, the resulting prototypes are functional, appear professional and all the deadlines put in place by my superiors were met.

## 6 Conclusion

The purpose of this thesis was to present how leakage current can be used to monitor the condition of an AC electric motor and to detail the stages of development of a device, the Talas Leaker, which utilises this principle.

From the experiments using an electric motor, desktop computer and table fan, a number of phenomena were observed. A reduction in current to a system will reduce the leakage current of that system. At a constant voltage, an increase in frequency results in a decrease of leakage current due to the capacitive reactance of the system, which reduces the current flowing to the system. At constant frequency, an increase in voltage results in an increase of leakage current. If the environmental factors causing damage (humidity, heat, pollutants) would suddenly cease to exist, and insulation would be in good condition, insulation resistance would quickly increase during the first few minutes due to the absorption current effect. As the contamination on the windings of a motor increases, insulation resistance decreases and capacitance of the motor increases. The lower the insulation resistance, the higher the capacitance of the windings.

The goals set at the beginning of the thesis were met, and the project is considered a success. The project resulted in five Talas Leaker prototypes, able to monitor an electric motor's leakage current online. The major benefits of this are the ability to prevent motor failure due to poor winding insulation resistance and ensuring the safety of personnel working close to the motor. The Talas Leaker has the potential to be used across various industries due to leakage current being a recurring issue among electric devices, deteriorating their insulation.

The limitations of the project were access to equipment and time constraints. If the project were to be carried out again, more time must be allocated to testing with the electric motor in different environmental scenarios. Further study that could be carried out is to find a solution for online separation of resistive and capacitive leakage currents for a better understanding of the winding insulation condition as well as the modifications outlined in section 5.1. Another future study to quantify the benefits of the Talas Leaker could be a life cycle assessment of extending the life of an electric motor using the device rather than waiting for breakdown, recycling/disposal of parts and purchasing new ones.

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## **Appendix 1. Assembly instructions and code installation**

The information in this section has been omitted due to confidentiality agreements.

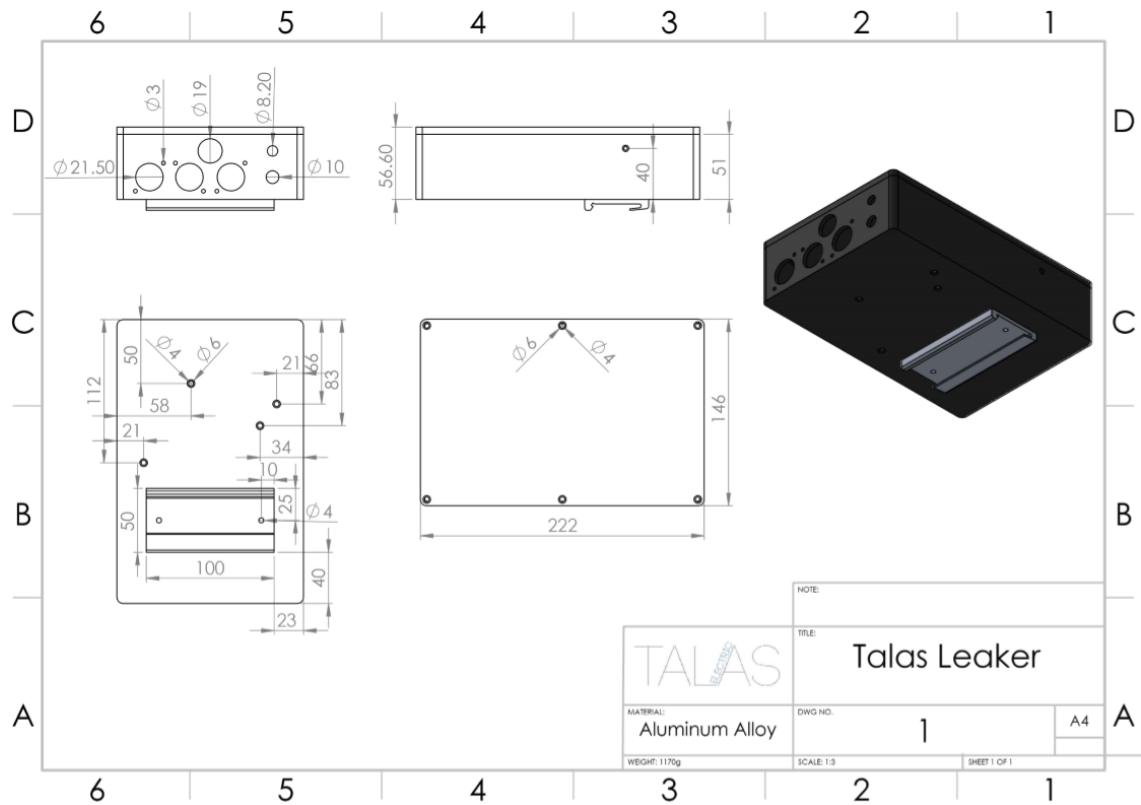
## **Appendix 2. Work schematic**

The information in this section has been omitted due to confidentiality agreements.

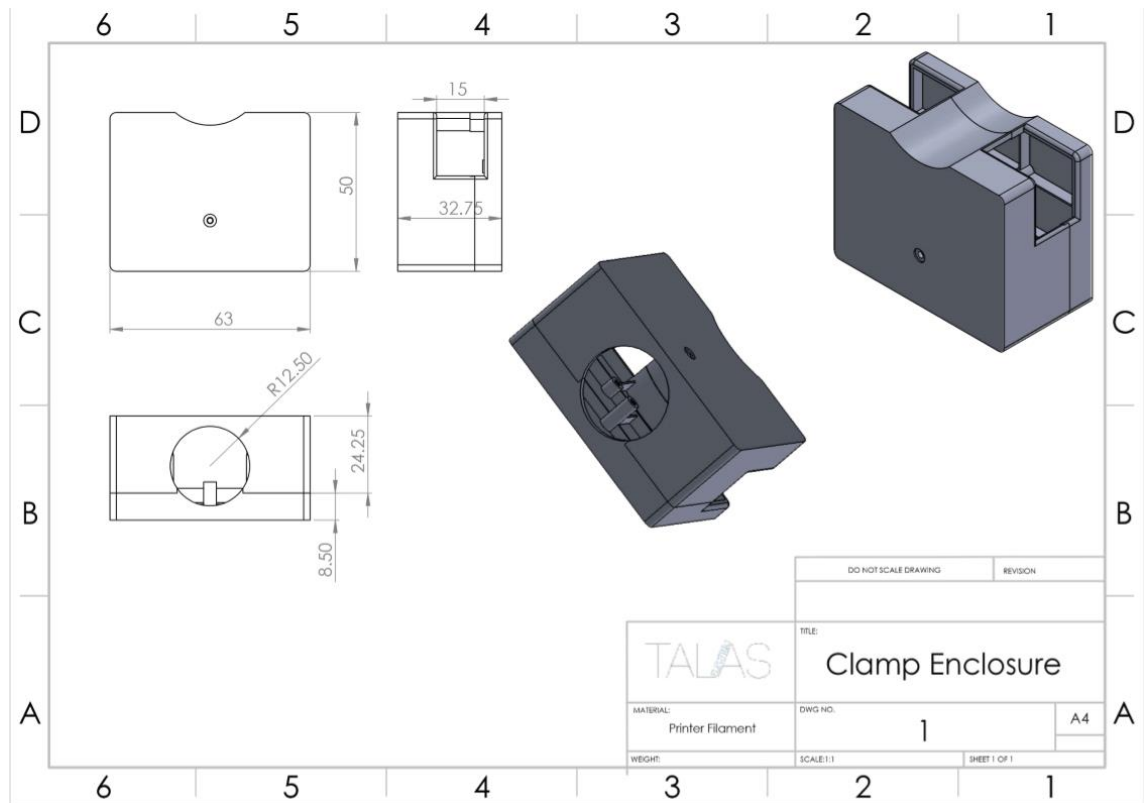
### **Appendix 3. Component specification**

The information in this section has been omitted due to confidentiality agreements.

Appendix 4. Talas Leaker 3D model and drawing



**Appendix 5. Handheld leakage clamp drawing**



## **Appendix 6. Internal wire specification**

The information in this section has been omitted due to confidentiality agreements.

## Appendix 7. External cable specification – work and client

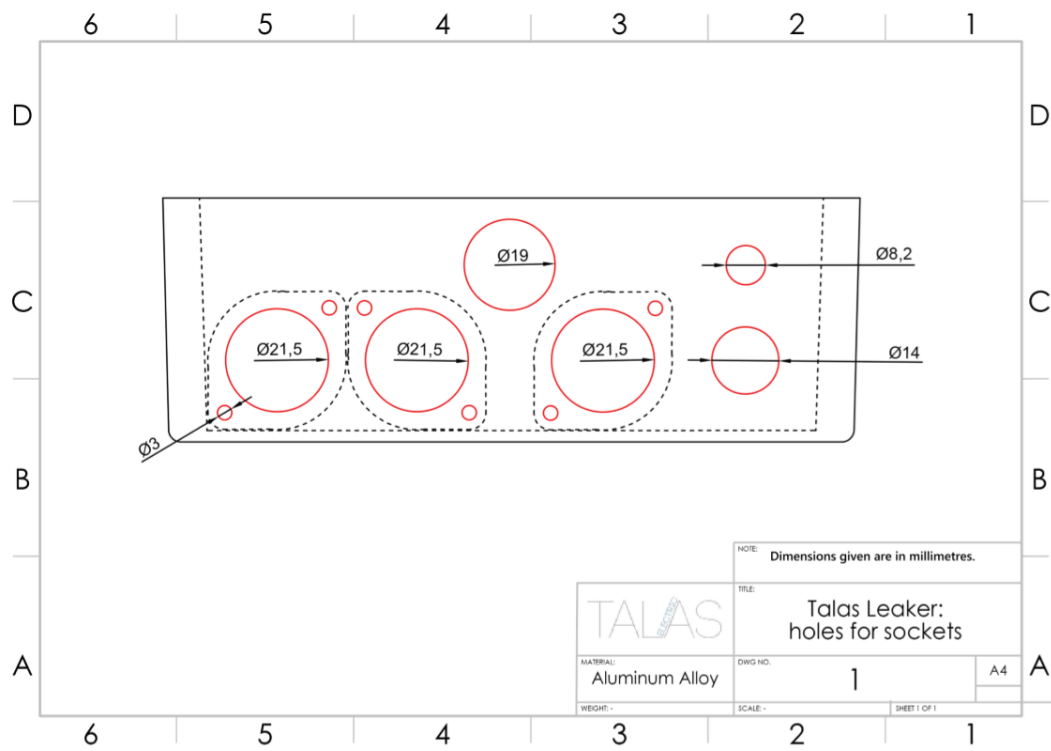
Talas Electric										
Talas Leaker External Cable Specification										
Internal Sockets							Plugs			
Socket Type	Name	Wire no.	From	To	Voltage	Cross Section (mm <sup>2</sup> )	Cable Type	Plug Type	Pin	External Wire
<a href="#">WEIPU SP2113/P3/2N</a> 3 pin Male socket	Power	1	Pin 1 3 pin male socket 230VAC from mains	Fuse holder	230VAC	0.75	Audio cable (300V)	<a href="#">Plug: Female; SP21; PIN:3</a>	1	Brown wire
		2	Pin 2 3 pin male socket 230VAC from mains	Button 1a SCI R13-244	0V		Blue wire (neutral)		2	Blue wire
		3	Pin 3 3 pin male socket 230VAC from mains	Frame	0V		Green-yellow wire		3	Green-yellow wire (PE)
<a href="#">WEIPU SP2113/S4</a> 4 pin Female socket	Modbus	9	Pin 1 4 pin female Modbus	WAGO +12VDC	12VDC	0.22	Shielded Tinned Annealed Copper Wire (red)	<a href="#">Plug: Male; SP21; PIN:4</a>	1	Yellow
		10	Pin 2 4 pin female Modbus	WAGO -12VDC	12VDC		Shielded Tinned Annealed Copper Wire (black)		2	White
		11	Pin 3 4 pin female Modbus	USB to RS485 converter, -3.3VDC	3.3VDC		Shielded Tinned Annealed Copper Wire (black)		3	Green
		12	Pin 4 4 pin female Modbus	USB to RS485 converter, +3.3VDC	3.3VDC		Shielded Tinned Annealed Copper Wire (red)		4	Brown
<a href="#">WEIPU SP2113/S2</a> 2 pin Female socket	Motor Start Command	7	Pin 1 2 pin female Start command	WAGO +5V	5V-230V (AC or DC)	0.22	Double Insulation Shielded Tinned Annealed Copper Wire (red)	<a href="#">Plug: Male; SP21; PIN:2</a>	1	Black wire #1
		8	Pin 2 2 pin female Start command	WAGO -5V			Double Insulation Shielded Tinned Annealed Copper Wire (black)		2	Black wire #2

Talas Electric								Talas Leaker is supplied with plugs and 2.5 metre cables for each plug							
Talas Leaker External Cable Specification for Client															
External Sockets						Plugs and Cables									
Socket Type	Socket Name	Signal type	Plug Type	Pin	External Wire	Voltage	Cross Section (mm <sup>2</sup> )								
<a href="#">WEIPU SP2113/P3/2N</a> 3 pin Male socket	Power	In: Power from mains	<a href="#">Plug: Female; SP21; PIN:3</a>	1	Brown wire	230VAC	1.5								
		In: Neutral from mains		2	Blue wire										
		In: PE		3	Green-yellow wire (PE)										
<a href="#">WEIPU SP2113/S4</a> 4 pin Female socket	Modbus	Out: RS485 + (B)	<a href="#">Plug: Male; SP21; PIN:4</a>	1	Yellow	3.3V	0.5								
		Out: RS485 - (A)		2	White	3.3V									
		Out: Power output for modem - 12VDC		3	Green	12V									
		Out: Power output for modem +12VDC		4	Brown	12V									
<a href="#">WEIPU SP2113/S2</a> 2 pin Female socket	Motor Start Command	In: Motor start command L1 or +	<a href="#">Plug: Male; SP21; PIN:2</a>	1	Black wire #1	5V	1.5								
		Out: Motor start command L1 or +		2	Black wire #2										

## **Appendix 8. Technical schematic**

The information in this section has been omitted due to confidentiality agreements.

## Appendix 9. Talas Leaker socket hole drawing



## Appendix 10. Talas Leaker 'Getting started' product card

