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Research on the Mechanical Quality of an Underground Cable Connector

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Abstract

A reliable electricity transmission network has a vital role in modern society. The long service life and the capital intensity emphasize the importance of distribution network design and selecting good quality components. The thesis addresses quality related factors in underground cable connectors. The connections in underground cable connectors are widely established by screwing. The performance and reliability of a connector are important aspects of quality. The reliability of underground cable connectors is determined by standardized tests. All in all, quality consists of every characteristic that makes the product fulfil the set requirements or the expectations of clients.

This thesis determines the structural elements that affect the quality of the screw coupling in an underground cable connector. Improving the feel of the screw coupling would enhance the quality perceived by the customer. In particular, the significance of thread tolerance of the screw is explored. A method is developed for measuring the dependency between the torque needed for tightening the screw and the force generated at the tip of the screw.

Based on the results of the torque-force tests and the ISO 965-1 standard, it is worth looking into utilizing 4h screws in conjunction with a 6H thread instead of 4g screws. In the tests 4h screws produced slightly more force at any given tightening torque. A screw coupling having a 4h screw felt firmer than a 4g screw. This is a corollary of the smaller clearance. Testing is needed with an actual connector body that utilises screws manufactured to meet the 4h tolerance.

Based on benchmarking, the feel of the screw couplings commonly have some free play. Small deformations or chips in the edges of the shearing point and tightening tool grooves affect the feel when turning the screws by hand. Disposing of these imperfections would enhance the quality perceived by a customer. Some phase of the tin coating process can apparently cause imperfections to the finished screw threads. The whole work process needs to be analysed to figure out and eliminate the exact cause or causes of the damages in the thread.

The scrutiny of the split connectors under a microscope revealed, inter alia, that the threads in many connector bodies deform under tightening of the screws. Some manufacturers use an internal thread crest shape that yields under loading. The microscope revealed a thread on which the thread bore and tapping may not be entirely concentric. Additionally, a crack noticed under the microscope on a thread of a connector body should be investigated. The internal threads call for further attention.

Keywords client quality, thread tolerance, shear-head screw

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Tiivistelmä

Luotettava sähkönsiirtoverkko on elintärkeä osa nykyaikaista yhteiskuntaa. Pitkän käyttöiän ja pääomavaltaisuuden vuoksi sähkönsiirtoverkon suunnittelu ja hyvälaatuisten osien käyttäminen on tärkeää. Tässä työssä käsitellään maakaapeliliittimien laatua koskettavia tekijöitä. Maakaapeliliittimien liitoksissa käytetään yleisesti ruuviliitoksia. Liittimen suorituskyky ja luotettavuus ovat tärkeitä laadun näkökulmia. Maakaapeliliittimien luotettavuus määritetään standardisoiduin testein. Kaiken kaikkiaan, laatu koostuu kaikista ominaisuuksista, joiden myötä tuote täyttää sille asetetut vaatimukset tai asiakkaan odotukset.

Tämä työ määrittää rakenteelliset tekijät, jotka vaikuttavat maakaapeliliittimen ruuviliitoksen laatuun. Ruuviliitoksen tuntuman kehittäminen parantaisi asiakkaan kokemaa laatuvaikutelmaa. Työssä tutkitaan erityisesti ruuvin kierretoleranssin merkitystä. Ruuvin kiertämiseen vaadittavan momentin ja ruuvin kärjessä syntyvän voiman välisen riippuvuuden mittaamiseksi kehitetään mittausjärjestely.

Momentti-voimamittausten tulosten ja ISO 965-1 –standardin perusteella olisi perusteltua harkita 4h-ruuvien käyttämistä 6H-kierteen kanssa 6g-ruuvien sijasta. Mittauksissa 4h-ruuvit tuottivat enemmän voimaa kaikilla kiristysmomentin arvoilla. 4h-ruuvia käyttävä liitos tuntui vankemmalta kuin 4g-ruuvia käyttävä. Tämä on seurausta pienemmästä välyksestä. On tehtävä testejä oikealla liitinrungolla käyttäen ruuveja, jotka on valmistettu 4h-toleranssin mukaisiksi.

Kilpailevien tuotteiden ruuviliitosten tuntumassa havaittiin yleisesti jonkinlaista välystä. Urista voi selvästi aiheutua epätasaisuutta ruuviliitoksen tuntumaan. Pienet epämuodostumat tai lastut ruuvien katkeamiskohtien ja kiristystyökalun urien reunoissa vaikuttavat tuntumaan ruuvia käsin pyöritettäessä. Urien reunojen epätäydellisyyksien poistaminen parantaisi asiakkaan kokemaa laatua. Jokin tinaukseen liittyvä työvaihe voi nähtävästi aiheuttaa epätäydellisyyttä lopullisiin ruuvikierteisiin. Kaikkia työvaiheita tulisi tarkastella, jotta kierteiden vaurioiden syy tai syyt saadaan selvitettyä ja poistettua.

Halkaistujen liitinten tarkastelu mikroskoopilla paljasti muun muassa, että monien liitinrunkojen kierteet muuttavat muotoaan ruuvia kiristettäessä. Jotkin valmistajat hyödyntävät sisäpuoleisessa kierteessä harjamuotoa, joka myötää kuormitettaessa. Mikroskoopilla havaittiin kierre, jossa reiän poraus ja kierteitys eivät näytä täysin samankeskisiltä. Lisäksi mikroskoopilla liitinrungon kierteessä havaittua halkeamaa on tutkittava. Sisäpuoleisia kierteitä tulee tutkia lisää.

Avainsanat asiakaslaatu, kierretoleranssi, katkeavakantainen ruuvi

Preface

This thesis is written for the Ensto Utility Networks business unit of Ensto Finland Oy. The company desired to identify the factors affecting the client quality of underground cable connectors. A particular goal was evaluating the effect of thread pitch in the screw coupling used in connectors.

I highly appreciate the valuable guidance my supervisor Matti Pietola has given me in writing this academic work. I wish to thank my advisor Hannele Kenkkilä for all of her extensive help in both practical arrangements and the literary work.

I wish to thank Antti Toivanen for helping especially in defining and achieving the goals of the practical research. Arne Liljeström has given me essential assistance in performing the measurements. I'm in great gratitude to my superior Timo Vikman who has enabled me to write this thesis for Ensto.

Also many others have offered me aid in completing my work. Thank you. It has been a joy to be a part of the work community at Ensto Utility Networks.

I wish to thank my parents who have supported me throughout my life.

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Matti Peltola

Contents

Symbols

D	[mm]	Major diameter of internal thread
D_2	[mm]	Pitch diameter of internal thread
D_3	[mm]	Minor diameter of internal thread
F_n	[N]	Normal force
F_s	[N]	Axial force
F_u	[N]	Tangential force
G		Tolerance position marking for metric internal threads
H		Tolerance position marking for metric internal threads
L		Long length of thread engagement
L_a	[mm]	Distance between connector and equalizer
L_b	[mm]	Distance between connector and equalizer
LH		Designation for a left hand thread
L_r	[mm]	Length of reference conductor
M_g	[Nm]	Tightening torque of a nut or a screw
M		Prefix for metric threads
N		Normal length of thread engagement
P	[mm]	Pitch of thread
Ph		Designation for multiple-start metric threads
R	[kN/Nm]	Ratio between torque and force
S		Short length of thread engagement
$\bar{X}$	[kN/Nm]	Mean value of variables
Z		Value of Normal distribution corresponding to a specific number
d	[mm]	Major diameter of external thread
d_2	[mm]	Pitch diameter of external thread
d_3	[mm]	Minor diameter of thread
d_r	[mm]	Distance between connectors
d_s	[mm]	Diameter of cylinder
e		Tolerance position marking for metric external threads
f		Tolerance position marking for metric external threads
g		Tolerance position marking for metric external threads
h		Tolerance position marking for metric external threads
k		Number of intervals in a histogram
n		Number of variables
u	[kN/Nm]	Minimum difference that needs to be detected
x		Marking separating the nominal diameter and pitch in thread designations
x_i		Variables in a sum
α		Level of significance
α_n	[°]	Flank angle
β		Probability of not rejecting a false null hypothesis
γ	[°]	Angle of thread
μ		Confidence interval
μ_g		Coefficient of friction
σ	[kN/Nm]	Standard deviation
σ^2	[kN^2/Nm^2]	Variance

Abbreviations

AFNOR	Association Française de Normalisation The French organization for national standardization
ATEX	Appareils destinés à être utilisés en ATmosphères EXplosibles A European Union directive describing the equipment allowed in an explosive atmosphere.
CE	Conformité Européenne European Conformity
CEN	Comité Européen de Normalisation European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
DIN	Deutsches Institut für Normung German Institute for Standardization
EC	European Commission
EFTA	European Free Trade Association
EMC	Electromagnetic Compatibility
EN	European Standard
EU	European Union
H^+	Positive hydrogen ion
H_2SO^4	Sulphuric acid
HCl	Hydrogen chloride
HD	Harmonization Document
HNO_3	Nitric acid
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
ITU	International Telecommunication Union
MBNQA	Malcolm Baldrige National Quality Award
NaCl	Sodium chloride
NF	Norme française French national standard
PAFF-model	Prevention, appraisal, internal failure, external failure
PF	Parallel piping thread
PT	Tapered piping thread
SESKO	Suomen sähköteknillinen standardisoimisyhdistys National Electrotechnical Standardization Organization in Finland
SFS	Suomen Standardisoimisliitto Finnish Standards Association
SI	International System of Units
TC	Technical Committee of the International Organization for Standardization
TQM	Total Quality Management
UNC	Unified National Coarse Thread
UNF	Unified National Fine Thread
ksi	Kiloponds per square inch, equivalent to 6.895×10^6 pascals
pH	Numeric scale specifying the acidity of an aqueous solution

1 Introduction

A reliable electricity transmission network has a vital role in modern society. In practice, electricity is transmitted to users via overhead lines or underground cabling. As a result of its location, underground cabling is not as vulnerable to natural phenomena as overhead lines. For the same reason the construction of underground cabling costs more than of overhead lines. (Lakervi, Partanen 2008)

The operating life of overhead lines is approximately 40 to 50 years and underground cables may be in use even 100 years. The long service life and the capital intensity emphasize the importance of distribution network design and component selection. (Lakervi, Partanen 2008) A reliable electricity network is built using the right techniques and good quality products (Pfisterer 2014).

When establishing electrical contacts force is required for flattening the distortions of contact surfaces. This lowers the contact resistance. Force is applied by crimping or screwing. Up to a certain saturation point, as more force is applied, the resistance decreases. (Pfisterer 2014) In underground cable connectors the connection is widely established by screwing.

This thesis is written for the Ensto Utility Networks business unit of Ensto Finland Oy. Ensto is a family business and international cleantech company specializing in the development, manufacture and marketing of electrical systems and supplies for the distribution of electrical power as well as electrical applications (Ensto 2015a).

1.1 Motivation

The performance and reliability of a connector are important aspects of quality. All in all, quality consists of every characteristic that makes the product fulfil the set requirements or the expectations of clients (Salminen 1989). Quality gives a significant competition advantage for a company (Pajunen 1990). Quality improvement efforts may induce costs but the improved quality leads to increased overall profits for instance through increased sales profit (Lehtonen 2004).

1.2 Scope and Objective

In this thesis quality is in the heart of the scope. In order to address quality related factors in underground cable connectors the concept of quality needs to be first sufficiently specified. The reliability of underground cable connectors is determined by standardized tests. Standardization is decisive for screws and fasteners of many types. On these grounds this thesis compiles relevant information concerning standardized testing of underground cable connectors, standardization of threads and standardization as a globally organized activity.

This thesis determines the structural elements that affect the quality of the screw coupling in an underground cable connector. In particular, the significance of thread tolerance of the screw is explored. A method is developed for measuring the dependency between the torque needed for tightening the screw and the force generated at the tip of the screw.

Potential ways for improving the quality of the screw couplings in underground cable connector are resolved. Connectors launched to the market should operate without problems. However, the feel of the screw coupling could often be improved to represent the performance of the connector. This would enhance the quality perceived by the customer. Underground cable connectors from a selection of manufacturers are evaluated. The thread tolerances of the connectors are identified and recorded. The mechanical operation of the screw couplings is observed based on practical examinations.

Lubrication is a relevant aspect in underground cable connectors. It is not in the scope of this thesis to explore different lubricants or lubrication methods. The operation of the connectors and screw couplings is observed from a mechanical point of view focusing on the thread tolerance. The effect of thread pitch is not tested. Standardized testing of underground cable connectors is not carried out within the framework of this thesis. The thesis excludes issues that involve material technology.

1.3 Structure

The structure of this thesis is following. Chapter 2 gives an overview on underground cable connectors. The structure, operation and manufacturing of a connector are presented. The chapter describes the requirements set by the application and operating conditions of an underground cable connector. The relevant standardized tests are covered.

Chapter 3 discusses quality. First, the evolution of the concept of quality is introduced. Secondly, the chapter defines quality according to present understanding and explains its significance for business. Finally, methods for improving quality are presented.

Chapter 4 focuses on standardization and threads. Standardization is discussed from the viewpoints of standardization organizations and standardization of threads. In addition, the chapter considers thread types other than the ISO 965 general purpose metric threads and reviews screw mechanics and the effect of thread pitch.

The relevant calculations are presented in chapter 5. The methods for expressing the central tendency and dispersion of the data are presented. Calculations are stated for defining the required number of test cycles. Formulas relating to the dependency between tightening torque and axial force are introduced. The chapter describes the calculations regarding the fit between internal and external threads. The data analysis of the test results is also explained.

Chapter 6 describes the testing arrangements for the thesis. First, the developed torque-force testing arrangement is described. Later, the chapter focuses on benchmarking of rival products. They are evaluated with precision measuring instruments and based on feel and visual findings.

Chapter 7 presents the results of the torque-force tests starting from the pre-test that defined the sample size for the primary tests. In addition to the torque-force tests, the benchmarking findings are demonstrated. The tolerances and thread feel of the rival products were examined. Furthermore, split threads were observed under a microscope.

The last chapter presents the results of the research. The results are interpreted and recommendations are given for improving the quality of the underground cable connector. Possible subjects for future research are suggested.

2 Product Information

This chapter gives an overview on underground cable connectors through presenting an example product. Along with the product characteristics, also the manufacturing methods, requirements set by the application and the standardized tests are covered.

2.1 Characteristics

A connector assembly is shown in figure 1. The connector in question is used for connecting medium voltage cables up to 36 kV. The main part of the connector is the aluminium connector body. Cables are inserted into the connector from both ends. There are plastic centring rings for both ends of the body. The connector has four screws for securing the cable ends.

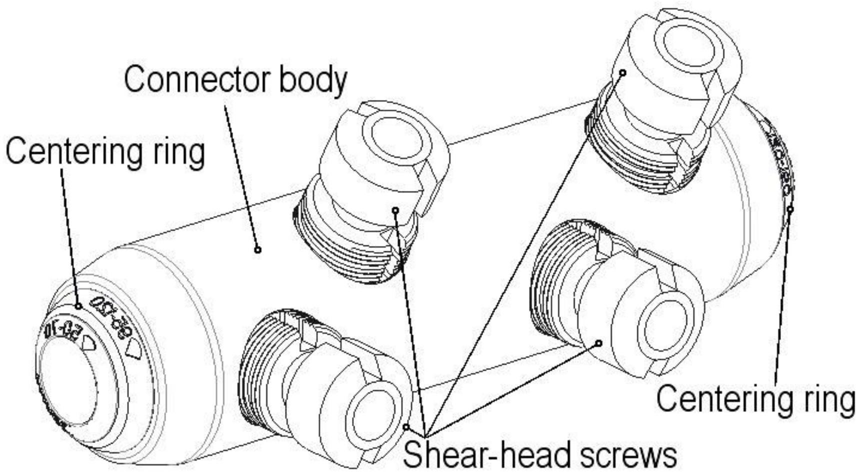

Figure 1 The underground cable connector consists of an aluminium body, polypropylene centring rings and shear-head screws.

Because of the shear-head screws no crimping tools are required. The required torque is achieved by tightening the screw until it breaks at the correct shearing point. The screw has three specified shearing points at which it can break off. The adapter that is needed for tightening the screw is supplied with the connector. (Ensto 2015c)

The connector can be used for aluminium and copper conductors. The conductors may be solid or stranded and they may have a sector shape or be circular. The cable core insulation may be plastic or paper. The possible nominal cross-sections of the conductor range from 70 to 240 mm^2. The connector can also be used with a 50 mm^2 cable. However, an aluminium filler piece is needed inside the connector. (Ensto 2014) The filler piece makes the connector work as intended also with a slightly smaller cable diameter than the range of the connector indicates. The filler piece can be used with both aluminium and copper conductors. (Ensto 2015b)

The polypropylene centring ring aligns the cable end to the centre of the boring in the connector body. The centring ring has an external thread that is used for attaching it to the connector body. The centring ring is used with round conductor diameters from 50 to 150 mm^2. When utilising the connector for round conductors in the range of 120 to 150 mm^2 a nozzle piece is to be cut away from the centring ring to enable the larger cable diameters. The nozzle can be cut using a knife. The centring ring is not needed and should not be used when connecting round cables in the range of 185 to 240 mm^2. The ratings are slightly different for connectors which have a sector shape. (Ensto 2014) Attaching the centring ring and cutting away the nozzle are shown in figure 2.

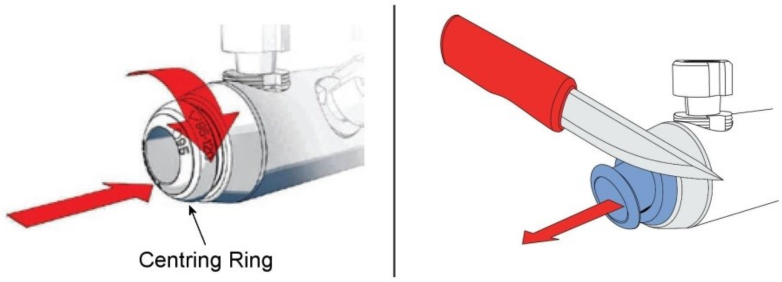

Figure 2 The centring ring is inserted to the end of the connector body and attached using a thread by rotating clockwise. The nozzle in the ring can be cut away using a knife to enable certain larger cable diameters. (Ensto 2014)

Installation errors can endanger the long-term stability of the contact. Contamination and oxide layers must be removed from the contact surfaces. The use of contact greases or pastes protects the contact zones against the ingress of air, water and salt and the oxidation and corrosion they would cause. The proper lubrication of the screw provides the optimal conversion of the applied torque into the required contact force. (Pfisterer 2014) The screws on the example connector are lubricated as a part of the manufacturing and assembly process. Hence there is no need to add any lubrication in the installation phase. Grease is applied to the cable boring of the connector body and the screws are greased using another lubricant.

2.2 Significance for the Electricity Transmission Network

The electricity distribution network has an essential role in the infrastructure of a society. Those using electricity expect the electricity distribution to be nearly free of interruptions. The share of the distribution network in the price of electricity is notable. In Finland this share is more than 30 percent of consumer prices and roughly 10-20 percent of the prices for industrial customers. Reliability and the quality of voltage are central for the overall quality of electricity. (Lakervi, Partanen 2008)

2.2.1 Characteristics of the Electricity Transmission Network

A considerable portion the overhead lines in Finland need to be replaced by the year 2020 due to aging. The generality of the electricity distribution networks consist of overhead lines. Underground cables are used especially in cities and smaller population centres. The structures and components used in electricity supply are costly. The operating life of overhead lines is approximately 40 to 50 years and underground cables may be in use for as long as 100 years. Choosing the suitable techniques for building and renewing the distribution networks is an essential resolution as the installed network may be in use till the end of the century. The length of the service life and the capital intensity emphasise the importance of distribution network design and component selection. (Lakervi, Partanen 2008)

On areas where population is growing rapidly also the loading of the electrical power network may grow several percent every year. As a result of this, the capacity of the network needs to be continuously increased by investing in new network construction. Yet, in rural areas the power consumption may even decline. Under these circumstances the reliability of all of the network components is imperative. (Lakervi, Partanen 2008)

Costs may be induced to the power distribution company not only from constructing and maintaining the distribution lines. The breaks in power distribution may be a result of a technical failure. Replacing a component may be needed. Legislation may also stipulate a compensation that has to be paid to the customer if the duration of a blackout is longer than a prescribed time. Considering the possible negative financial consequences, investing in reliability beforehand is unquestionably worthwhile. Also the manufacturer of the used components has to ensure the quality of its products. Bad product quality may lead to claims for compensation and returning of articles. (Lakervi, Partanen 2008) The component manufacturer's point of view and quality costs in general are discussed in more detail in chapter 3.

An underground cable network costs clearly more than overhead lines. This is most of all due to the cost of burying the cables underground. (Elovaara, Haarla 2011) The cost of underground cable installation is highly dependent on the type of the soil and the disposal of other possible underground structures, such as water systems. (Lakervi, Partanen 2008) Cables are laid into trenches, ducts or even in tunnels which may be the case especially in large cities. Also the cost of the needed accessories, connectors and cable lugs form a considerable item of expenditure. Using the more costly underground cables has got some advantages compared to overhead lines. The advantages include less need for space, less disturbances for the surroundings and less vulnerability to weather. Underground cables can also tolerate temporary overloading longer because the surrounding soil cools the cable longer than air. Nevertheless, in addition to the higher price there are also other drawbacks which include longer repair times, being prone to careless excavation work, larger capacitance and poorer tolerance to long-term overloading. (Elovaara, Haarla 2011)

Comparing the overall costs of overhead lines and underground cables is not straightforward. Depending on the surroundings the cost of a 110 kilovolt underground cable connection is approximately 3 to 10 times as expensive as a corresponding overhead line in Finland. In cities using underground cables is often the only viable option because there simply is no space for overhead lines. Lately reliability reasons, landscape protection and the desire to constrict electromagnetic fields have led to an increase in favouring underground cables. Underground cabling is spreading to the outskirts of cities an even outside residential areas. Crucial medium voltage and 130 kilovolt connections are being converted into underground cables to improve reliability. The Danish department of energy has decided that the state-owned energy company must cable every overhead line connection up to 150 kilovolts. Also every new 400 kilovolt connections in Denmark outside Jutland will be constructed using underground cabling. (Elovaara, Haarla 2011)

2.2.2 Importance of Correct Techniques

Contacts are often unfoundedly regarded as the weak points in electricity distribution. The majority of the failures could be prevented as they are usually consequences of faulty installation or using low-grade connectors. In recent years the energy markets have evolved rapidly. Supply areas have merged, new cable materials have been introduced and larger cable cross-sections have been launched to meet the increment of energy demand. A single distribution network may include as much as seven different cable types. There is a clear need for reliable contacts that can be flexibly used in a variety of applications. (Pfisterer 2014)

Crimping is an effective technique for installing connectors but it does have a history of causing power failures. Crimping methods are based on specific conductor sizes. There are specific sleeve cross-sections and tools for each conductor cross-section. To reduce the cost of cables they are produced more and more efficiently. The wires inside the cable are pressed together more tightly which makes the cable more compact. Consequently the need for insulation material is reduced. All this leads to a situation where cables with the same cross-section specification may in reality vary in form. When in a hurry, those fitting the connectors tend to use the next best thing available. This may lead to imperfect installations. (Pfisterer 2014)

The requirements for contact quality still vary incredibly widely from one country to the next. In Germany an end user has to endure a power failure for seven minutes per year. In the United States the figure is nine hours and in Thailand fourteen hours. (Pfisterer 2014)

For a cable connector the purchase price may be minuscule when assessing the total cost through the entire service life. Installation, logistics and maintenance play a substantial role also. The costs incurred by failures and compensation are factors that have to be carefully evaluated. The operating equipment worth several millions may depend on a contact worth €10. A €50 product with a failure rate of 1 % and an installation time of one hour may achieve €115,000 in annual cost. A €70 product of higher quality with a failure rate of 0.5 % and an installation time of one hour may cost annually €97,000. However, a €90 product with a failure rate of 0.5 % and an installation time of half an hour may result in an annual cost of €85,000. There are proper reasons for selecting contact technologies using quality, material and contact design as criteria. (Pfisterer 2014)

Creating a good connection is straightforward as long as everything is done right. Two flat surfaces placed on top of each other do not form a good connection as there are virtually only a few electrical contact points created in the peaks of the surface roughness. The situation above leads to very high contact resistances. In order to lower the contact resistance, force is needed for flattening the distortions, driving the peaks of the surfaces into each other and creating a galvanic contact. Force is applied by crimping or screwing. The more force is applied the lower the resistance becomes. This works until a saturation point is reached. After this point the resistance stays the same even if more force is applied. The resistance level achieved by applying force does not start increasing immediately after tightening has ended. This is because of the contact hysteresis: it takes more force to make a contact than to maintain it. The contact force has to fall below a specific limit before the contact resistance increases again. For aluminium the limit is 10 N/mm^2. There is basically no need for retightening the screw connections. Shear-head screws are an excellent tool for eradicating the temptation of retightening. (Pfisterer 2014)

There are a few simple things that lead to a good connection. The contact area must be clean, which is best made sure by brushing with a wire brush. The contact surfaces then need to be protected from oxidizing by applying contact protection paste. (Pfisterer 2014) Dry surfaces have the highest friction, whereas oiled threads have the lowest.

When a lubricant is applied to fasteners, friction is decreased. If the threads are lubricated, more of the torque applied contributes to the axial tension. This means the parts are held together with a greater force and the fastener is stressed more. (Abdo 2011) Especially the screws need to be greased to achieve the optimal contact force. Some manufacturers supply the products with pre-greased screws that are ready for installation. The last phase that needs to be performed correctly is tightening the screws to the specified torque. (Pfisterer 2014)

If something has gone wrong in the installation phase the contact resistance may increase exponentially during operation. In addition to ensuring the correct installation, there are requirements for the design of contact terminals. The terminal design must guarantee that a minimum contact force of approximately 20 % of the optimal initial force is maintained over a period of three to four decades. (Pfisterer 2014)

The higher the initial resistance of a contact is the shorter the life of the connection. Resistance causes heating and the connection resistance grows with an increasing thermal load. If a connection operates in a cable trench the initial resistance may increase due to soil or other impurities which contaminate the contact. Crimped contacts may suffer from a wrong combination of conductor and sleeve material. The main materials used in the power supply industry are copper and aluminium. Across the world different conductor and connector material are making contact with each other. If an aluminium conductor is crimped with a copper sleeve the premature failure of the contact is inevitable. Aluminium expands more under heat than the copper sleeve can yield. At some point the yield strength of aluminium is exceeded because of the mechanical stress. The conductor no longer returns to its original shape after cooling. After several heating and cooling cycles the contact quality deteriorates and eventually the contact fails totally. (Pfisterer 2014)

The contact force in any pair of mechanically connected material reduces over time. As a matter of fact, the contact force diminishes by 20 to 30 % during a few minutes after the installation. Yet, the lifespan of a contact may be 50 years. As long as the remaining contact force is high enough the contact works as intended. Elasticity has to be built into the body of the terminal to make sure the connection lasts through the desired service life despite thermal breathing. The length, width and thickness of the connector components are important. When they are set right the required contact force can be achieved without permanent plastic deformation of the connector body. (Pfisterer 2014)

2.3 Operating Conditions

Contacts may also age due to galvanic corrosion. (Pfisterer 2014) Pure aluminium has very good corrosion resistance due to the protective passive layer. In general, aluminium alloys are much less corrosion resistant. The environment, alloy composition, temperature treatment and the presence of contaminants are major factors influencing the deterioration rate. Aluminium alloys show pitting when corroded. Aluminium is sensitive to galvanic corrosion. In particular, contact with copper must be avoided. (Bijen 2003) Aluminium has an electronegativity value of -1.66 V and copper is slightly electropositive at +0.34 V. If an electrolyte is introduced to the connection the potential difference of 2 V will cause a weak flow of current. This corrodes the more electronegative metal. (Pfisterer 2014)

Even small copper particles can cause considerable problems. Pitting corrosion of aluminium cladding elements has been observed within 200 metres distance from overhead electric railway and tramlines. Also contact with wood that is impregnated with copper salts must be avoided. Direct contact with steel or iron can also enhance corrosion. (Bijen 2003) Electrical insulation between the above-mentioned metals is required for eliminating the problem. Cathodic protection is used for aluminium alloys. This is done by coating using pure aluminium or another less noble alloy. Electrolytic oxidation or anodization is another method for protecting an aluminium surface. (Bijen 2003) Insulation has to be taken care of. Even a few millimetres wide brush stroke of insulating resin at the junction of the material is sufficient. (Pfisterer 2014) Tin coating of aluminium connector components is explained in further detail in chapter 2.5.2

Terminals must also be designed and operated according to the expected loads. Component aging is promoted by high power loading. It is more and more common that the loading is heavily increased in networks that may have thirty year old connections. (Pfisterer 2014) Renewable energy, especially wind energy, causes variation in the amount of energy transmitted in a certain section of the network. During peak production older network sections are under high loading. (Boyle 2007)

Atmospheric conditions corrode metals. Hydrogen is formed at the cathode. Generally the reduction of H^+ ions dominates in atmospheric corrosion. This is because the atmosphere is slightly acidic and there is an adequate water film present at the metal surface to maintain an electrotechnical current. Occasionally climates are so dry that this film is not formed and for instance the corrosion of steel and cast iron is negligible. Salt and dust particles can promote condensation of moisture. Salt and dirt can locally increase the moisture conditions at metal surfaces and decrease the electrical resistance of the water film. Consequently, the corrosion rate increases. SO_2 and the chloride content in the air largely determine the corrosivity of the environment. The corrosivity of the atmospheric environment in the western countries has actually decreased during the past twenty years. This is due to the concurrent decrease in the amount of dust particles and the SO_2 concentration in the air. Chloride in the air is bound to aerosol particles and is restricted to maritime areas. The concentration decreases substantially within the first ten kilometres from the coast. (Bijen 2003)

Underground corrosion processes are similar to those occurring in the atmosphere or in water. The rate of corrosion depends eventually strongly on the water content and on the salts dissolved in the water. In water-saturated soil and in dry soil the corrosion can be neglected. Between these two extremes corrosive situations can be formed. Air is usually sufficiently available in sandy soils to maintain the corrosion process and often pit corrosion occurs. Clay soils often have high water content. They contain less air which restricts corrosion. Dissolved salts increase the conductivity of the soil and increase the corrosion rate. The electric conductivity is an important criterion for the corrosivity of soils. (Bijen 2003)

2.4 Standardized Testing

Underground cable connectors are tested in a few precise ways to ensure the products perform in the difficult conditions for decades without failures. Many of the conducted tests are standardized tests and some are voluntary testing performed by the manufacturer. Type testing according to the IEC 61238-1 standard is required to gain the certificate needed for launching the product on the market. Various other tests are done to verify product quality and in order to react to reclamations. (Kortelainen 2015) The following chapter discusses testing according to an IEC (International Electrotechnical Commission) standard and an EN (European Standard) standard. Standardization and the organizations concerning it are covered in more detail in chapter 4.

2.4.1 Electrical Testing According to the IEC 61238-1 Standard

One of the most relevant tests for underground cable connectors is the test according to the IEC 61238-1 standard (Kortelainen 2015). A new version of the standard has been sent to a circulation for comment and it is yet to be implemented (Lappalainen 2016). The standard concerns compression and mechanical connectors for power cables for rated voltages up to 30 kV. The object of the standard is to define the type test methods and requirements, which apply to compression and mechanical connectors for power cables with copper or aluminium conductors. Although it is not possible to precisely define the service conditions for all applications, the standard defines two broad classes of connectors: Classes A and B. Class A connectors are intended for electricity distribution or industrial networks in which they can be subjected to short-circuits having relatively high intensity and duration. As a consequence, Class A connectors are suitable for the majority of applications. Class B connectors are for networks in which overloads or short-circuits are rapidly cleared by the installed protective devices, such as fast-acting fuses. Class A connectors are subjected to heat cycle and short-circuit test. Class B connectors are subjected to heat cycle test only. (IEC 2003)

The standard defines the electrical test assembly consisting of six connectors which are connected in series. The standard also defines the essential used terms. The connectors shall be fitted in accordance with the manufacturer’s instructions on a bare conductor or on a conductor that has had the insulation removed before assembly. The connectors form a test loop together with the corresponding reference conductor. According to the standard a reference conductor is a length of unjointed bare conductor or conductor with the insulation removed. The reference conductor is included in the test loop and it enables determining the reference temperature and reference resistance. (IEC 2003)

The potential between the strands of stranded conductors may cause errors in measuring electrical resistance. Welded or soldered equalizers may be used to overcome this problem and to ensure uniform current distribution in the reference conductor. Welded or soldered equalizers are the recommended methods to ensure reliable measurements. The test loop may be of any shape provided that it is arranged in such a way that there is no adverse effect from the floor, walls or ceiling. Retightening of bolts or screws of the connectors under test is not permitted. (IEC 2003) The electrical test setup is presented in figure 3.

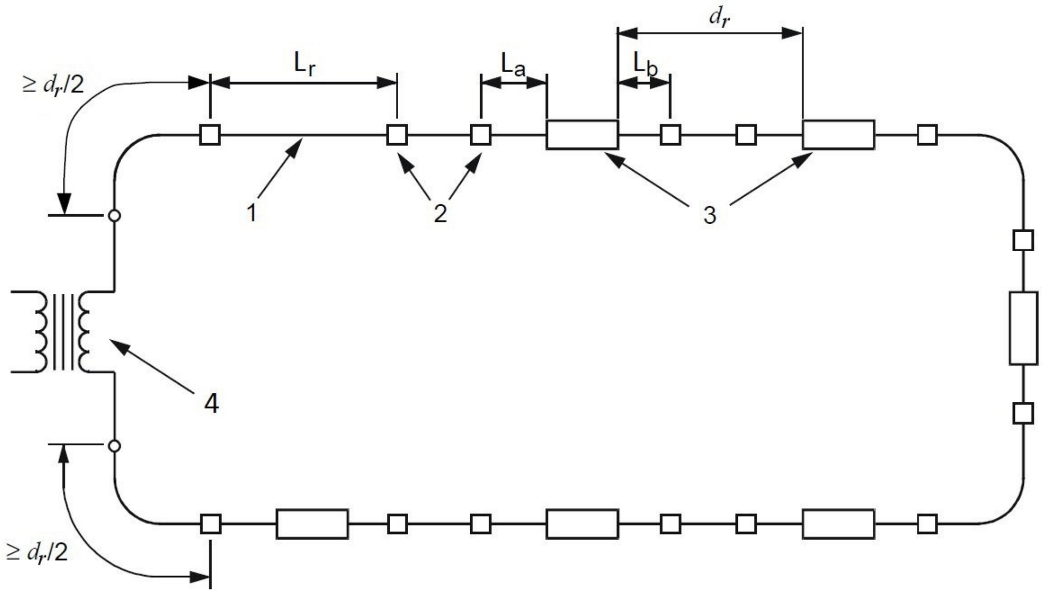

Figure 3 The proportions of the electrical test setup consisting of the main reference conductor (1), the equalizers of stranded conductors (2), the connectors (3) and the current source (4). The distance between connectors (d_r) and the distances between connector and equalizers (L_a, L_b) depend on the nominal diameter of the cable and are specified in the standard. The length of the reference conductor (L_r) has to be at least the sum of L_a and L_b. (IEC 2003)

The short-circuit test of Class A connectors can be made easier by composing a test loop that can be dismantled. In this case, the technology of the sectioning connections shall be such that they do not influence the measurements, particularly from the point of view of temperature. (IEC 2003)

A connector which covers a range of cross-sectional areas shall be approved, if satisfactory results are obtained on the smallest and the largest cross-sectional area. Using thermocouples is the recommended method for measuring the temperatures of the connectors and the reference conductors. In the case of the reference conductor, the thermocouple shall be positioned at the mid-point and securely located either in a small hole drilled in a solid conductor, or by sliding it under the strands of the outer layer of a stranded conductor. In the case of the connectors, the thermocouple may either be inserted in a small hole drilled into the main body of the connector or be secured to the outside surface. The resistance measurements shall be performed under steady temperature conditions of both the test loop and test location. The ambient temperature shall be between 15 °C and 30 °C. (IEC 2003)

The recommended method is to pass a direct current of up to 10 % of the heat cycling current through the connectors and the reference conductor without increasing the temperature and to measure the potential difference between specific potential points. The ratio of potential difference and direct current is the resistance between those points. (IEC 2003)

The heat cycling test is performed using alternating current. The first heat cycle is used for determining the reference conductor temperature to be used for subsequent cycles and also to identify the median connector. Current is circulated in the test loop until the reference conductor reaches 120 °C at equilibrium. Equilibrium means the temperature of the reference conductor and the connectors do not vary more than ±2 K for 15 min. If the temperature of the median connector is equal to or greater than 100 °C the reference conductor temperature in subsequent tests shall be 120 °C. If not, the current is increased until the median connector temperature reaches 100 °C at equilibrium. The reference conductor temperature is not to exceed 140 °C. If the temperature of the median connector does not reach 100 °C, even with a reference conductor temperature of 140 °C, the test shall be continued at that temperature. (IEC 2003)

The object of the second heat cycle is to determine the heat cycle duration and temperature profile which will be used. Current is circulated in the loop until the reference conductor temperature defined in the first cycle is reached and the median connector temperature is stable within a band of 2 K over a 10 minute period. The reference conductor temperature is the control parameter for keeping the temperature profile during the heat cycle test. The reference temperature time heating profile shall be recorded and used for all subsequent cycles. An elevated current may be used to reduce the heating period. The duration of the elevated current depends on the conductor's nominal cross-section. The current shall thereafter be decreased or regulated to a mean value that ensures stable conditions during the median-connector control period. After the heating period, follows a period of cooling to bring the temperature of all connectors and the reference conductor to a value ≤35 °C. (IEC 2003) The cooling can be sped up using fans (Kortelainen 2015). The standard states that accelerated cooling has to act on the whole loop and use air within the ambient temperature limits. (IEC 2003)

1000 heat cycles are to be made in total. After the cooling period of certain cycles, the resistance and temperature of each connector and each reference conductor shall be recorded. The maximum temperature of each connector during the cycle just prior to or following the resistance measurements shall also be recorded. Class A connectors are measured in total 14 times and Class B connectors 12 times during the 1000 test cycles. There are specified intervals for the measurements but a tolerance of ±10 cycles can be used. (IEC 2003)

Six short-circuits are applied after the 200^{th} heat cycle for Class A connectors. The short-circuit current level shall be such that it raises the reference conductors from a temperature of ≤35 °C to a temperature between 250 °C and 270 °C. The duration of the short-circuit current shall be 1 s (tolerance +0.5 to -0.1) with a maximum current of 25 kA. If the required short-circuit current exceeds this value a longer duration ≤5 s with a current between 25 kA and 45 kA shall be used. After each short-circuit, the test loop shall be cooled to a temperature ≤35 °C. (IEC 2003)

The six connectors have to satisfy the set requirements. The values analysed include initial and mean scatter, change in the resistance factor, resistance factor ratio and maximum temperature. If one connector out of the six does not satisfy one or more of the requirements, a re-test may be carried out. In this event, all six new connectors have to satisfy the requirements. If more than one connector out of the six does not satisfy one or more of the requirements, no retest is permitted and the type of connector is deemed as not conforming to the standard. (IEC 2003)

2.4.2 Mechanical Testing According to the IEC 61238-1 Standard

The purpose of the mechanical tensile tests is to ensure an acceptable mechanical strength for the connections to power cable conductors (IEC 2003). The test is a type of a tensile strength test. A pulling force tests if the cable ends slip inside a connector.

The test shall be made on three additional connectors identical to those used for the electrical test. The connectors are installed according to the manufacturer's instructions. The conductor lengths (d_r), between connectors or between connector and tensile test machine jaws, shall be ≥500 mm. (IEC 2003) The principle of the test setup is demonstrated in figure 4.

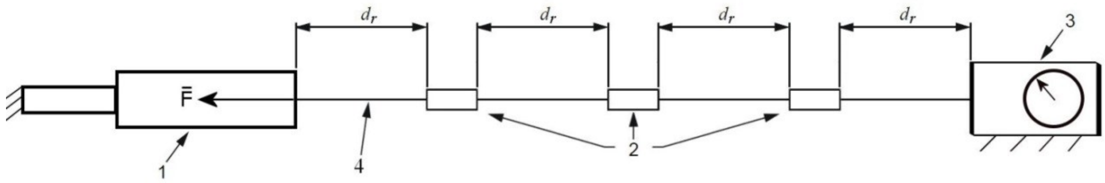

Figure 4 Force (F) is subjected to the cable (4) using the instrument (1). The lengths of the cable are connected with the cable connectors (2). The conductor length (d_r) is ≥500 mm. The force is measured with the measuring instrument (3). The test determines if there is slip inside a connector.

The rate of application of the load shall not exceed, firstly, 10 N per square millimetre of cross-sectional area and, secondly, the value in table 1. If the connector is tested electrically for conductors with a different cross-sectional area, the different conductor variations shall be tested individually, in accordance with table 1. (IEC 2003)

Table 1 The tensile force used in the mechanical test of a cable connector. (IEC 2003)

Conductor material	Tensile force (N)
Aluminium	40 × A** ; maximum 20,000
Copper	60 × A** ; maximum 20,000
** A = nominal cross-sectional area (mm^2)	

The correct force is applied to the test assembly and then maintained for 1 min. The requirement for passing the test is that no slipping occurs during the one minute of steady loading. (IEC 2003) The company policy is to test also how much force it takes to finally cause slipping of the wire in the connector (Kortelainen 2015).

2.4.3 Corrosion Aging Testing According to the EN 50483 Standard

The standard EN 50483 defines the test requirements for low voltage aerial bundled cable accessories. Part 6 of the standard defines the environmental tests, in particular the corrosion and climatic ageing tests. The objective of these tests is to predict the behaviour of cable accessories when subjected to sun radiation, to pollution and weather conditions, including humidity, spraying water, heat and cold. These tests are performed when the products contain parts protected with a metallic coating or metallic parts, which are exposed to the atmosphere. (CENELEC 2009) The test procedure according to EN 50483 is not aimed for underground cable connectors and is not required in type testing. However, as a part of product development projects underground cable connectors can be subjected to the environmental testing in consonance with the standard. (Karjalainen 2016)

The standard defines two corrosion aging tests: a salt mist test and a gas atmosphere test. The basic principle of the salt mist test is exposing the samples to a neutral salt spray. The concentration of the salt spray is 5 % sodium chloride (NaCl). Cycle duration is seven days. The gas atmosphere test exposes the samples to a humidity-saturated atmosphere rich with sulphur dioxide (SO_2) and precise conditions of temperature and pressure. (CENELEC 2009)

There are two methods for the gas atmosphere test. According to the first method, the samples and supports are installed in a hermetic test chamber, with a humidity-saturated atmosphere in the presence of sulphur dioxide. The initial concentration of SO_2 is 0.0667 %. The test chamber is to be made of inert material. After closing the chamber, sulphur dioxide is introduced from either a gas bottle or using a specific reaction in the chamber. (CENELEC 2009)

Each period, or basic module, comprises a weekly sequence. Seven 24 hour cycles are performed. Each cycle includes an eight hour exposure with saturated humidity and high sulphur dioxide atmosphere and a 16 hour exposure at the laboratory atmosphere. Exposure to laboratory atmosphere can be achieved by opening the chamber door. The intention of this phase is to allow clean air to circulate around the test samples. During the eight hour period, the temperature is raised to 40 ± 3°C. During the 16 hour period the chamber remains at ambient temperature and finally the water and sulphur dioxide atmosphere is renewed to the concentration specified earlier. (CENELEC 2009)

According to the second method for the gas atmosphere test, the test samples are subjected to a cyclic corrosion test consisting of a one hour period of drying and a one hour period of fog. The test consists of 500 cycles (1 000 hours). The fog period is performed at ambient temperature, while the drying time is performed at a higher temperature. The used salt solution consists of 0.05 % sodium chloride (NaCl) and 0.35 % ammonium sulphate $(NH_4)_2(SO_4)$ by mass. The pH of the solution shall be between 5.0 and 5.4. (CENELEC 2009)

The apparatus for salt spray testing consists of a fog chamber, a salt solution reservoir, a supply of suitable conditioned compressed air, one or more atomising nozzles, specimen supports, provision for heating the chamber and the necessary means of control. The material of construction has to be such that it is not affected by the corrosiveness of the fog. The chamber designed must ensure that no drops of the solution that accumulates on the ceiling of the chamber fall on the specimen being tested. The nozzle or nozzles shall be directed so that none of the spray can directly hit the test specimen. (CENELEC 2009)

During the fog period, no heating is applied to the cabinet. The fog exposure is carried out at 24 ± 3°C. During the drying-off period the temperature throughout the exposure zone reaches and remains at 35 ± 2°C within 45 minutes of switching from the fog period to the dry period. The test samples are not cleaned between the test cycles. The samples shall be cleaned at completion of the test. (CENELEC 2009)

After finishing the environmental tests and between different environmental tests when carried out as a sequence, the samples are cleaned, unless stated otherwise. When the specimens are exposed successively to a neutral salt spray and then to a humidity saturated atmosphere with sulphur dioxide, the procedure shall be seven cycles of 24 hours in salt, no cleaning, seven cycles of 24 hour in sulphur dioxide and then cleaning. Cleaning is done by using running tap water and then by using demineralised water. The temperature of the water must not exceed 35 °C. The samples are dried either by shaking by hand or using air blast to remove droplets of water. (CENELEC 2009)

An additional immersion test can be carried out when this is agreed between the customer and the supplier. In order to minimise testing, when agreed, this test shall be carried out during the mandatory heat cycle tests as provided in the fifth part of the EN 50483 standard. There are two methods for the additional immersion test. In both of them the samples are immersed to a solution. In the first method a saline solution is maintained at 29.22 g/l concentration of NaCl throughout the test. In the second method an acid solution for the test shall contain sulphuric acid (H_2SO_4), nitric acid (HNO_3) and hydrogen chloride (HCl) dissolved in distilled water in order to obtain a pH value equal to 2. (CENELEC 2009)

2.4.4 Climatic Aging Testing According to the EN 50483 Standard

The standard defines two methods for conducting a climatic aging test. In the first method the test subjects are exposed to a combined cycle of climatic constraints: ultraviolet radiation, humidity, water spray and temperature extremes. The test according to the second method principally exposes the test subjects to ultraviolet radiation. (CENELEC 2009)

The light source has to produce a spectrum that is as close as possible to the solar spectrum at ground level. The energy absorbed by the samples is determined with a black standard thermometer. The test chamber contains a rotating sample rack. A ventilation system produces air circulation around the samples in order to reduce the rise of surface temperature. The speed of rotation of the rack is between one and five turns in a minute. Sprinkling is carried out by one or several rain injectors spraying the front face of every sample. The light beam is produced by a cylindrical lamp with a xenon arc. Filters for the lamp eliminate wavelengths lower than 270 nm in order to provide a spectrum close to that of the solar spectrum. The power supply of the lamp is adjusted so that a desired average value of radiation energy is achieved. (CENELEC 2009)

The climatic aging test according to the first method consists of a number of identical weekly cycles. During the cycles there are different periods. During the periods the samples experience various levels of humidity, temperature and exposure to radiation. The specimens are exposed to radiation both with and without sprinkling. Sprinkling is performed with and without radiation. Sprinkling cycles usually include only a few minutes of sprinkling and mainly waiting without sprinkling. The temperature is varied during the tests. The lowest temperature during the cycles is -25°C and the highest 70°C. (CENELEC 2009)

The climatic aging test according to method two consists of a number of identical daily cycles. The duration of each cycle is 24 hours, with 20 hours of irradiation and 4 hours of darkness, repeated as required. The temperature rises to 55 ± 2°C within two hours of the start of the irradiation period and is maintained at this temperature throughout the irradiation period. During the darkness period the temperature within the enclosure falls at an approximately linear rate within two hours and is then maintained at 25 ± 2°C. (CENELEC 2009)

2.5 Manufacturing Methods

The manufacturing of the connector body and screw is presented based on Ensto's connector. Both of the components are machined out of a solid billet. First the machining phase is presented, followed by a description on the coating of the metal components. The centring ring of the connector is an injection moulded plastic component whose production method consists simply of the injection moulding process. The molten plastic is fed to an injection mould where the component takes it final form. The mould is typically cooled using cold water.

2.5.1 Machining

The connector body is machined using a single machining centre. The raw material for the connector body is a round aluminium bar. The diameter of the bar matches the outer diameter of the finished connector body. The machining centre starts the machining process by cutting a billet from the bar using a circular saw. The billets are attached to a revolving carrier that conveys them from one machining stage to the next. After cutting, the cable holes are drilled in. Then the holes are tapped. In the following stage the screw holes are drilled. Then the ends of the body are levelled and simultaneously the edges are rounded. This is done concurrently for both ends with contoured milling tools. The last machining step is the tapping of threads to the screw holes. It is noteworthy that the screw holes are not in line but, instead, the screws are inserted from two different angles. To allow the threaded screw holes to have two different angles, the connector body is rotated also in the clamp of the carrier between machining stages. (Tiala 2015)

The machining of the screw is done using a self-acting lathe with multiple tools. The raw material for the screws is a round aluminium bar which is fed into the lathe. The machining starts by drilling the centre hole to the screw. Next the groove between the threaded section and the screw-head is machined. The following stage is levelling the head and chamfering the top edges using a contoured milling tool. Then the grooves for the adapter used for tightening the screw are milled. The work piece is stationary during the milling of the longitudinal grooves. The following stage is milling the grooves for the shearing points. Threading the screw is the second to last stage. Lastly, the screw is cut to the correct length simultaneously creating the shape of the screw tip. (Tiala 2015)

During the machining of the connector body and the screws, the workpieces and the machining tools are cooled and lubricated using a continuous oil spray. The machined components are collected to a tray after the final machining phase. A certain number of products are tested during specific intervals to make sure the process is working as intended and the products meet the set requirements. The threads are checked with a thread gauge. A torsion test is conducted for the screws to verify they break at the correct torque. (Tiala 2015)

It has been detected that the mechanical properties of the aluminium bars vary slightly. The hardness of different bars is not necessary identical. Also the hardness of the material may vary in a single bar from one end when compared to the other. Usually the variation is still within the set limits. Nevertheless, if the machining process is not tuned according to the actual mechanical properties of the material it may cause problems in the finished product. (Tiala 2015)

2.5.2 Coating

Products are often finished by coating. The reasons for coating include increasing the mechanical or chemical durability of the surface and reducing friction. Coatings may also be used for improving the conductivity in terms of heat and electricity. In addition to the previous, coatings can promote the appearance of products. The overall reason for coating a component can consist of a combination of the motives mentioned above. (Aaltonen, Aromäki et al. 2009) This chapter discusses electroplating universally and tin coating that is a relevant electroplating method for underground cable accessories. First the cleaning process that precedes the coating is described.

After machining the possible remains of metal chips are sifted using a sieve or a blower. The components are then placed into baskets in which they are cleaned from oil and grease using an alkaline solution. The baskets spin and rock or in some cases stay still during the washing process. After washing the parts are rinsed and then dried using hot air. (Alatalo 2010)

By using electricity a metal coating can be deposited from a saline solution to a piece that conducts electricity. When a metallic salt is dissolved to water the salt dissociates to positive metallic ions and negative acid radicals. Direct current is used for charging the component to be coated. The component is given a negative charge and so it works as the negative electrode, the cathode. The coating material forms the positive electrode, the anode. As a direct current passes through the electrolyte, the positive metallic ions find their way to the cathode, where the electrons compensate for the positive charge of the metallic ions. The metallic coating settles to the cathode. The acid radicals are drawn by the anode. The acid radicals dissolve more coating metal to the electrolyte. Often there are multiple anodes. Using dissolving anodes maintains the concentration of the metallic ions in the solution. In some cases insoluble anodes are used and, instead, the coating metal is added to the solution as a soluble compound. Chemicals are added to the electrolyte for keeping the pH stable. (Aaltonen, Aromäki et al. 2009)

The metallic coating settles to form an equally thick layer on a level surface. If there is unevenness in the original surface it is present in the coated surface also. Imperfections may occur around sharp edges. A thicker layer of coating is formed on outer corner and a thinner layer in the inner corners. These corner imperfections can be removed by using auxiliary cathodes. (Aaltonen, Aromäki et al. 2009)

Complex salts are typically used for metal coatings since they create a fine-grained particle structure that forms a flawless surface layer. The coating best adheres to a surface that has a similar crystal structure. If there is a significant difference between the crystal structures of two materials an intermediate layer is used. The electrolyte is circulated through filtering in order to remove impurities and stabilize the temperature.

The properties of the surface being coated play a meaningful role in the end result. The following surface imperfections impair the coating result:

- tears and breaches
- pores and inclusions at the surface
- corrosion damages and residual stress
- surface defects and surface roughness formed during machining (Aaltonen, Aromäki et al. 2009)

Metals can be put in order based on the resting potentials. When comparing two metals on this scale, the one ranked higher is nobler. The potential difference of two metals defines the pace of electrochemical corrosion between them. The metal which is more electronegative, or less noble, corrodes. (Aaltonen, Aromäki et al. 2009)

A difference in the coefficient of heat expansion of the base metal and the coating may cause the coating to break. The base metal determines how well the coating withstands impacts and compression. The thickness of the coating should be clearly more than the height of the surface roughness in a surface that undergoes heavy loading. This is to make sure the coating does not fracture nearby the peaks of the surface roughness. (Aaltonen, Aromäki et al. 2009)

Hydrogen is always present in the electroplating process. The hydrogen is in its atomic form and it moves freely about in the metal structure. As the temperature drops hydrogen returns to its molecular form. This damages the metal structure as the hydrogen pushes its way to crazes and pores. This unwanted phenomenon can be prevented using a suitable heat treatment after the coating process. (Aaltonen, Aromäki et al. 2009)

Tin coating is a method used in demanding applications. Tin coatings hold their colour well. Tin oxides are not dangerous. A noteworthy factor for some applications is that the coating emits no taste. Tin coated sheet metal can be soldered and bent. Thus preserve cans are made out of tin coated sheet metal. Tin suits particularly well for coating electrotechnical components. Tin in itself is an expensive metal but it is widely used for coating because of its properties. Tin is easy to use and it protects many metals against atmospheric corrosion. (Aaltonen, Aromäki et al. 2009)

Tin coatings are an economic solution that enhances reliability. When the wax-like tin surface is penetrated it retreats and then closes up around the contact points once the contact has been made. Finding the right balance is important: the coating thickness and material must be chosen to suit the need. The desired electrical properties, such as low contact resistance, the necessary corrosion protection and reasonable costs form the appropriate ensemble. (Pfisterer 2014)

The tin coating of aluminium components proceeds as follows. The components are placed in drums for the duration of the process. The process starts with rinsing and an acidification in nitric acid followed by rinsing. The first coat that goes on to the components is a thin film of zinc that is chemically precipitated to their surface. The components go through rinsing and acidification and get another film of zinc. After appropriate rinsing the components are copper plated in an alkaline solution. The electroplating process uses copper plates as the anodes and the components act as the cathode. After the coper layer follows rinsing and, finally, an acidic tin bath. Tin plates act as the anodes and the components as the cathode. The parts are once again rinsed and next toppled from the drums into a centrifugation container that is used for drying the parts. (Alatalo 2010)

3 Quality

Quality can be contemplated from many viewpoints. Doing research on the quality of an underground cable connector calls for understanding on every aspect of quality. First, the evolution of the concept of quality is introduced. Secondly, the chapter defines quality according to present understanding and explains its significance for business. Finally, methods for improving quality are presented.

3.1 History of Quality

Originally the development of quality focused on improving the accuracy of the production. The goal was in making mass production more effective and raising customer satisfaction. The focus has subsequently moved more towards ensuring customer satisfaction instead of avoiding mistakes in production. (Salminen 1989)

Systematic quality control evolved in the late 19th century along with the development of the mass production industry. The transition from small workshops into mass production facilities caused a dramatic increase in the losses resulting from poor quality. It was easy for a blacksmith to fix a slight flaw right away. In a factory a small error may have been repeated thousands of times. The idea of mass producing standardized interchangeable components calls for quality control. The ideas of desired values, tolerances and testing were born based on observations and experiments. (Lehtonen 2004)

Quality control advanced from observation based testing into a technical special field. This entailed collecting data from the production processes and analysing it using statistical methods. The modern quality control originates to the theories of Walter A. Shewhart who worked in Bell's laboratories in the early 20th century. He developed the classification of defects in quality to common and special causes. (Lehtonen 2004) In 1924 Shewhart's control chart was published. It is a statistical tool for determining whether the variation of the process is caused by controllable or uncontrollable variation. (Salminen 1989)

Shewhart's pupil William Edwards Deming worked in the field of statistics and he brought statistical quality control to Japan in the 1950s (Lehtonen 2004). Deming detected that Shewhart's ideas were not very well accepted among the people working in production. Deming understood this was due to the lack of statistics education. He organized statistics training for thousands of engineers and technicians already in the 1940s. His lessons went in especially in Japan. (Salminen 1989) The first comprehensive quality handbook was written by Joseph Juran. Juran's ideas about managing quality using rational planning and organising were welcomed in Japan. In this context quality evolved from a manufacturing concept into a comprehensive management system known as total quality management (TQM). (Lehtonen 2004)

The economic boom which had started from the reconstruction after the Second World War came to a halt in the early 1970s due to the monetary and oil crises. The growth of demand ceased. Mass production divided into smaller sections and the importance of a wide portfolio increased. Quality became a notable selling point. (Lehtonen 2004)

The Japanese export industry used quality control to its advantage in order to catch up with the western industry. Especially Japanese cars and consumer electronics gained significant international success starting from the middle of the 1970s till the beginning of the 1990s. The market share of Japanese cars in the United States rose to 25 percent. This was above all on account of better quality. The Japanese cars had fewer manufacturing flaws and the range of models satisfied the customer needs. Applying the principles of Japanese-style TQM began to spread widely as a consequence of this. Two major systematizations of modern quality control were born: the excellence frameworks and the ISO 9000 family of quality management systems standards. (Lehtonen 2004)

Over several decades quality awards have sparked the birth of many excellence frameworks. Quality awards have been established to accelerate quality improvement. Some of the best-known quality awards are the Japanese Deming Application Prize instituted in 1951 and the Malcolm Baldrige National Quality Award that was issued in the United States for the first time in 1988. (Evans, Lindsay 2008)

3.2 Basic Concept of Quality

This thesis pursues improving the perceived quality of the underground cable connector. To determine, what the perceived quality consists of, the whole concept of quality is first considered. This chapter gives a general definition for what quality comprises of.

The formation of quality can be divided into smaller sections in multiple ways. Quality consists of every characteristic that makes the product fulfil the set requirements or the expectations. The components that together form the quality of a physical product can be broken down as seen in figure 5. (Salminen 1989)

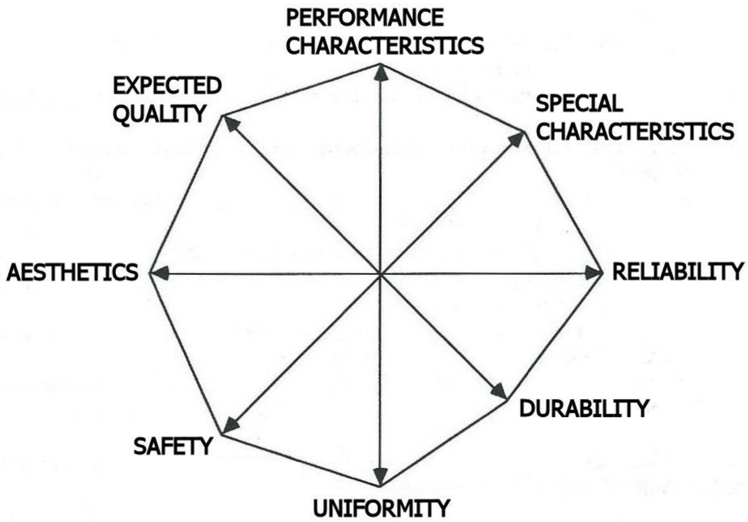

Figure 5 The quality of a product consists of several components. (Salminen 1989)

The performance characteristics of a product are often measurable values, such as force or speed. Special characteristics may include product specific requirements, such as modularity or resistance to specific conditions. The reliability of a product can be defined by calculations, measurements or estimations. It can for instance reflect the mean time between failures or serviceability. Durability is seen as the operating life of the product in the specific use and operating conditions. To determine the uniformity, the product is compared to standards or to other units in case of manufacturing defects.

Safety rests upon preventing risks that might be harmful to the users or the environment. Safety improvements may include safety devices and shields or insulation. The aesthetics arise from the appearance of the product. The shapes, colour and also the surface finishing play a key role in the aesthetics. The expected quality of a product is based on advertising, the company image, earlier experiences and competing products. (Salminen 1989)

The quality of a product can be observed from many viewpoints. Quality can refer to how the finished product corresponds to the plans. Quality can also be related to how the product performs in the purpose of use it is intended for. Figure 6 shows how the concept of client quality consists of multiple factors. (Lehtonen 2004)

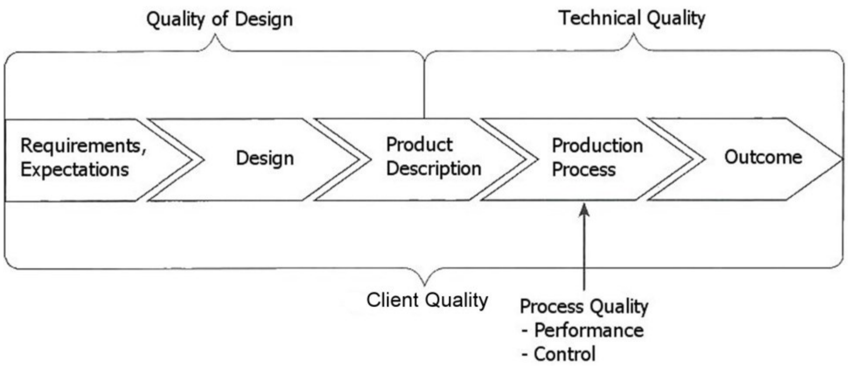

Figure 6 The concept of quality can be divided into sections. The quality of the design and the technical quality together form the client quality. (Lehtonen 2004)

3.2.1 Quality of Design

Designing starts from the concept development phase, when functions and specifications are being determined. When product specifications are finalized the development team makes trade-offs between desired performance characteristics. (Ulrich, Eppinger 2008) The quality of the design is determined by how well the original idea is translated into drawings or other types of design. How accurately the product can repeatedly be manufactured defines the production process quality. Design has a significant role in the manufacturability of the product. (Lehtonen 2004)

Early in the design process usually only an approximate bill of materials with estimates of costs can be compiled. Later these estimates become more and more accurate and the focus of the development team is directed to the right area. The process is iterative. It is not unusual to improve the design of the product and to recompute the manufacturing cost estimate dozens of times before agreeing that it is good enough. When estimating component costs one has to consider whether standard or custom parts are used. Assembling incurs labour costs and possibly costs for equipment and tooling. The so-called overhead costs include support costs, such as material handling, purchasing or shipping, and indirect allocations which are difficult to allocate to a specific product. Indirect allocations, such as the salary of security guards, contribute to the cost of the product even though they are not directly linked to the products. All of the relevant cost drivers have to be taken into account in the design phase. (Ulrich, Eppinger 2008)

The designer should understand the capabilities and constraints of the production process. A negligent designer may specify a small internal corner radius on a machined part without realizing that creating such a feature requires special manufacturing methods which are expensive. Sometimes such costly part features are not even necessary for the components function. It is often possible to design a component which achieves the same performance but is easier and cheaper to manufacture when compared to the original design. Sometimes the fabrication process can be simplified by redesigning the product. For example, the fabrication approach termed the net-shape strategy produces a part that is very close to the final requirement. Net-shape methods include approaches such as moulding, casting, forging and extrusion. Only minor additional processing, such as drilling and tapping a hole or cutting to length, is needed. (Ulrich, Eppinger 2008)

For most products, assembly accounts for a relatively small portion of the total cost. Yet, good design can maximise the ease of assembly and reduce costs at least to some extent. Factors such as self-aligning components and reducing the need of flipping over the assembly during working make the assembly process straightforward. Sometimes redesigning can even totally remove the need of assembly. (Ulrich, Eppinger 2008)

The design work occasionally has to balance between the end result quality and reducing costs. Consequently the design team must bear in mind the many dimensions of quality that are important for the product. The development time can be precious as well. Thus design decisions must be evaluated not only based on their effect on the manufacturing cost but also for their impact on the development time. (Ulrich, Eppinger 2008)

3.2.2 Technical Quality

Quality is very often seen as technical quality which describes the capability of the production process to perform the intended task. That is to say, technical quality stands for the equivalence between the plan and the realization. Complete equivalence can be pursued by controlling the manufacturing process as thoroughly as possible. Isolating the possible sources of error from the system is a way of improving the technical quality. Components and materials can be checked. Moisture, dirt and unfavourable temperature can be resolved. Standardization, automation and learning help in preventing human errors. If the process is not under control and produces random outcomes there is variation. Quality control aims to reduce variation and the losses that usually result from it. The process may be affected by random external interferences, or special causes. The other possible causes of variation are internal reasons, or common causes. (Lehtonen 2004)

The basic presumption of technical quality in an industrial context is that a product is manufactured or a service is repeated multiple times. A series of products is produced as the manufacturing process is repeated multiple times. The objective is that every repetition is uniform and the end results are identical. (Lehtonen 2004)

3.2.3 Client Quality

Client quality or interactive quality describes how the end result evolves to match the expectations or the agreements. It reflects the suitability of the product for the intended use. The client and the supplier interact through the project to form the result. Deliverables are the relevant results of an open process. A deliverable can be any product, service or information which can be acquired and utilized. The deliverables can be compared to the original goal and purpose. (Lehtonen 2004)

As seen earlier in figure 6, client quality is comprised of multiple sections. It relates whether the idea, plan and the production were suitable for the purpose of use. (Lehtonen 2004) Client quality is what the company offers and delivers to the client. Thus client quality is one of the major competitive tools on the market. (Pajunen 1990)

It may be difficult for a customer to acquire facts concerning the quality of rival products. When this is the case, the mental picture is formed based on the elements which are easy to distinguish. The customer usually considers properties like reliability and durability to be the most important aspects. Yet, one is often forced to rely on subjective experiences and mental images over the products. Performance and special characteristics, aesthetics and customer service have a considerable impact on the quality perceived by the customer. Factors such as spare parts and installation or maintenance services significantly affect the client quality of a service-oriented product. (Pajunen 1990)

How the customer perceives the quality of a company in relation to competitors is significant for the competitiveness of the company. This relative quality consists of four sections: firstly, the personal needs, emphasis and expectations of the customer, secondly, the actual quality of the products and service of the company, thirdly, the actual quality of rival solutions and fourthly, other factors that may affect the opinion of the customer. These other factors can include availability, advertising, sales, own experiences and those of others, published comparison tests, brand recognition and image or brand in general. (Pajunen 1990) The impact of quality on the competitiveness of a company is discussed in more detail in the following chapter.

3.3 Quality as a Competitive Factor

As mentioned earlier, quality can be an important selling point for companies. This chapter focuses on illustrating why quality is such an asset for business.

3.3.1 The Basis of Competitiveness

The competitiveness of a company measures how successful the company is compared to other companies in the same area of business (Salminen 1989). The perceived quality can be based on the value of the product. The value rests upon the relation between the features and the costs related to the product. Instead of true quality it is more a matter of how the customer sees the quality and how it influences the purchase decision. Price and the related costs are usually the most significant single factor affecting the purchase decision. This has to be taken into consideration when discussing quality as a competitive factor. (Pajunen 1990)

The best value for the customer is provided by the product that offers the most compared to the price. Usually products are compared in groups. One approach is to compare products inside the same price group and choose the best. Another way is to compare products which have the same characteristics and choose the most affordable. It may be difficult for a customer to obtain reliable information concerning the properties of the products. Different quality aspects and other properties may be given a numerical grade. These grades can be weighted and compared to the costs in order to decide the most favourable option. These comparisons are a pragmatic tool also for companies in assessing their competitiveness. (Pajunen 1990)

Based on assessments and market research a company has to decide what the most desirable combination of quality and cost is. If the relative quality compared to rival products is higher sales are promoted. (Pajunen 1990) Of course, the price cannot be raised unboundedly, not matter how good the product is. The customer must feel the quality is worth paying for.

Quality has high significance for Finnish companies. High labour costs and the prevailing conditions for mass production reduce the competitiveness when compared to rivals operating in other countries. Many internationally well-known Finnish companies have based their success on high quality. (Salminen 1989)

3.3.2 The Cost of Quality

Companies which have thoroughly investigated the possibilities of improving quality have discovered that quality related problems have to do with roughly 20-40 % of the turnover. Such a high share can be explained by considering also all of the indirect costs throughout the whole company. Faults related to quality may cause wasting of labour, material, components, transportation and machine time. Analysing the problem, planning and implementing the needed repairs are extra work. Indirect waste of time may result from redoing plans, schedules and work. Indirect costs result from longer turnaround time and buffer stocks established in case of defects. Also the actual production capacity is lowered and capital is tied to redundant work as a consequence of poor quality. (Pajunen 1990) Unplanned services, claims for compensation and returning of articles may lead to loss of sales and of reputation which are hard to quantify (Lehtonen 2004). High quality reduces financial losses resulting from returns, rework and scrap. Productivity and profits are increased. (Evans, Lindsay 2008)

Better quality increases profits also because of another distinct reason: better quality leads to more satisfied customers. Satisfied customers lead to increased sales volumes. This has also an effect on the pricing basis. (Lehtonen 2004) High-quality products help a company to stand out from the rest of the field. Satisfied customers will gladly sustain the business relations. The word concerning quality products will spread. (Evans, Lindsay 2008)

Internal failure costs arise from a defect inside the production system. The defect in question may be an unplanned stoppage, material loss, energy loss or fixing mistakes. External failures consist of the failures which occur in the user end and in operation. These include unplanned services, claims for compensation and returning of articles. A model used often for lowering the cost of quality is the PAFF-model (prevention, appraisal, internal failure, external failure). The operations and quality are defined and appraised. Error prevention and checking is developed. The quality of the operations is constantly monitored. As the efforts to improve quality begin the necessary actions often first increase costs. This can be seen as a good investment if error costs are diminished. Once the new practice takes root the costs will mainly return to original. (Lehtonen 2004)

Error costs tend to be costlier the later they are discovered. The following rule of thumb has been stated to apply to electronics: the effect of a defect in the quality of a basic component may be tenfold every time it proceeds to the subsequent phase. Therefore the fault of a close to worthless component may for instance lead to costs that are thousandfold compared to the price of the faulty component. (Lehtonen 2004)

Prototyping may be used for reducing costly iterations. A good example can be given from manufacturing a moulded component. If a moulded part fits poorly with its mating parts, the mould tooling may have to be rebuilt. Investing time and money to prototyping can reduce the probability of more expensive remedial actions. Prototyping can be used for improving the quality of the end result as parts can be tailored to be more precise and functionality can be fine-tuned. It depends on the project whether physical or analytical computer models are the feasible option for prototyping. In some cases testing using a comprehensive prototype is advisable and sometimes a focused prototype for testing a single function is sufficient. Taking time to build a prototype may enable more rapid completion of a subsequent step or tasks may be completed concurrently. Time and money can be saved by performing tests on a prototype while waiting for the actual production version of a component. (Ulrich, Eppinger 2008)

3.4 Improvement of Quality

This chapter discusses some key methods and frameworks for improving quality. First, the people-focused Total Quality Management system is covered. Later the relevance of quality management awards through the Malcolm Baldrige National Quality Award and the principles of the ISO 9000 certification process and the Six Sigma quality management framework are discussed. The Malcolm Baldrige National Quality Award and the ISO 9000 certification process are the two frameworks that have had the most impact on quality management practices worldwide (Evans, Lindsay 2008). More recently, Six Sigma has gained ground as a quality management framework (Evans, Lindsay 2008).

3.4.1 Total Quality Management

The term total quality management (TQM) was developed by the Naval Air Systems Command to describe its Japanese-style method for improving quality. Total quality management is based on three central principles: firstly, the focus of operations must be on the customers and stakeholders; secondly, everyone in the organization must participate and work as a team; thirdly, the process focus must be supported by continuous improvement and learning. Total quality management means an organization actively pursues to identify customer needs and expectations. The organization seeks to build quality into work processes by utilising the knowledge and experience of its workforce. The ambition is to continually improve every aspect of the organization. (Evans, Lindsay 2008)

The impression of value and satisfaction of the customer are influenced by the whole chain of purchase, ownership and service experiences. Meeting specifications, reducing defects and resolving complaints is not enough. A company must incorporate product development and delight the customer. The company needs to rapidly respond to changing consumer and market demands. A company close to its customers is able to correctly interpret the customer needs and may even be able to foresee them. Internal customers are also important for insuring quality. When employees see themselves as customers to and suppliers of other employees the importance of their work becomes concrete. Still, the company has to broaden its view even further. The whole society is a stakeholder for a world-class organization. Commitment to employees must be demonstrated and social responsibility must not be ignored. (Evans, Lindsay 2008)

The participation of the entire workforce and seamless teamwork is a blueprint for good quality. Employees must have the tools for making good decisions and the freedom and encouragement to make contributions. Employees should participate in decisions which affect their operations. Total quality management calls for coordination between organizational units, such as design, engineering and manufacturing or manufacturing, shipping and sales. Partnerships with unions, customers, suppliers and educational organizations create mutual benefits. For instance, offering education to a supplier can improve the work quality of the supplier, thus improving also the quality of the customer company itself. (Evans, Lindsay 2008)

Continuous improvement encompasses small and gradual improvements, as well as considerable and swift improvements. Improvement may come in many forms. Value to the customer may be complemented. Errors, defects, waste and the costs related may be cut down. Productivity and effectiveness in the use of all resources can be increased. Responsiveness and cycle time performance can be developed. Response time, quality and productivity objectives should be estimated together. Notable simplification of work processes may be needed for considerable improvements in response time. The process often leads to improvements in quality and productivity. Improvements rely on learning. An organization must assess the conducted processes and revise plans and practises based on the assessment findings. (Evans, Lindsay 2008)

The three principles of TQM are supported by an integrated organizational infrastructure, an assortment of management practices and a set of tools and techniques. Infrastructure means all of the main management systems. TQM requires the following management aspects: customer relationship management, leadership and strategic planning, human resources management, process management, information and knowledge management. The actions that are carried out in the different segments of the infrastructure are the practices. An example of a human resources practice is determining employee satisfaction. The tools consist of graphical and statistical techniques. They are used for collecting data, analysing results, planning operations and solving problems. A graph showing how the amount of scrap material has evolved is an example of a tool. (Evans, Lindsay 2008)

3.4.2 The Malcolm Baldrige National Quality Award

The Malcolm Baldrige National Quality Award (MBNQA) has acted as one of the most influential incentives for total quality around the world. Quality awards are usually established to spur companies to improve quality and productivity while obtaining a competitive edge. The award-winning achievements work as an example for others. (Evans, Lindsay 2008)

MBNQA has evolved into an inclusive National Quality Program in the United States. Up to three companies can receive an award in the original categories of manufacturing, small business and service. Newer categories include non-profit education and health care. The award examination is based upon the Criteria of Performance Excellence. It consists on seven hierarchical categories, items and areas to address. Table 2 presents the categories and their composition. (Evans, Lindsay 2008)

Table 2 The categories of the Malcolm Baldrige National Quality Award. (Evans, Lindsay 2008)

Category	Matters examined
Leadership	How do the organization's senior leaders address values, directions and performance expectations? Their focus on customers and other stakeholders, empowerment, innovation and learning is also examined.
Strategic Planning	How does the organization develop strategic objectives and action plans? How are the chosen objectives and plans deployed and how is progress measured?
Customer and Market Focus	How does the organization determine the requirements, expectations and preferences of customers and markets? How does the organization build relationships with customers and determine the key factors leading to customer acquisition, satisfaction, loyalty, retention and to business expansion?
Measurement, Analysis and Knowledge Management	How does the organization select, gather, analyse, manage and improve its data, information and knowledge assets.
Human Resource Focus	How do the organization's work systems and employee learning and motivation enable employees to develop and utilize their full potential in alignment with the organization's overall objectives? Also examined are the organization's efforts to build and maintain a work environment and employee support climate conducive to performance excellence and to personal and organizational growth.
Process Management	The category examines the key aspects of an organization's process management, including key product, service and business processes for creating customer and organizational value and key support processes involving all work units
Business Results	The category examines the organization's performance and improvement in key business areas: customer satisfaction, product and service performance, financial and marketplace performance, human resource results, operational performance and governance and social responsibility. Also examined are performance levels relative to competitors.

Even though the award itself is given only to the chosen few, its Criteria for Performance Excellence provide a framework. This framework guides the integration of total quality principles and practices to any organization. The guidelines and criteria of the awards can be used by businesses, industrial, governmental and other enterprises in evaluating their own quality improvement endeavours. (Evans, Lindsay 2008)

3.4.3 ISO 9000 Quality System Standards

The International Organization for Standardization (ISO) established a series of written quality standards in 1987. The object of the standards was to standardize quality requirements for the European countries within the common market and those wishing to do business with them. Organizations certified under the ISO 9000 standards are assured to have quality equal to their peers. The standards are recognized by about 100 countries. (Evans, Lindsay 2008)

ISO 9000 defines quality system standards, based on the hypothesis that certain generic characteristics of management practices can be standardized. Further, a well-designed, well-implemented and carefully managed quality system is anticipated to provide confidence that the outputs will meet customer expectations and requirements. The standards were created to meet five objectives:

1. Achieve, maintain and seek to continuously improve product quality in relationship to requirements.
2. Improve the quality of operations to continually meet the stated and implied needs of the customers and stakeholders.
3. Provide confidence to internal management and other employees that quality requirements are being fulfilled and that improvement is taking place.
4. Provide confidence to customers and other stakeholders that quality requirements are being achieved in the delivered product.
5. Provide confidence that quality system requirements are fulfilled. (Evans, Lindsay 2008)

Quality related documentation is defined in the standards. Compliance through auditing should lead to continuous improvement. Many products that are sold in Europe require product certification to assure safety. ISO certification may be needed for acquiring a product certification. Meeting the standards is becoming a requirement for international competitiveness. (Evans, Lindsay 2008)

The standards address developing, documenting and implementing procedures. The goal is in ensuring consistency of operations and performance in the production and service delivery process. The standards comprise the following documents:

1. ISO 9000 – Fundamentals and vocabulary. The document provides fundamental background information and defines the key terms used in the standards.
2. ISO 9001 – Requirements. The specific requirements for a quality management system are given. The requirements must be met in order to gain third-party certification.
3. ISO 9004 – Guidelines for Performance Improvements. The guidelines of the document assist organizations in improving their quality management systems beyond the minimum requirements in ISO 9001. However, no requirements which have to be followed are imposed. (Evans, Lindsay 2008)
4. ISO 19011 - Guidance on internal and external audits of quality management systems (ISO 2015).

The original intention of the ISO 9000 standards was to be a guideline to be used in two-party contractual situations and for internal audits. Yet, they rapidly evolved into criteria for companies that wanted to certify their quality management. Third-party auditors such as laboratories or other accreditation agencies would certify the company, and this certification is accepted by all of the customers of the company. In any case, ISO 9000 provides a set of adequate methods for initiating a quality system. It is an excellent starting point for companies with no formal quality assurance program. (Evans, Lindsay 2008)

The original ISO 9000:1994 series standards consisted of 20 central elements of a basic quality system. It included such things as management responsibility, product identification and traceability, process control, inspection and testing, training, internal quality audits and statistical methods. Nevertheless, the requirement was only that the organization has a documented verifiable process in place for ensuring that it consistently produces what it says it will produce. It was possible to comply with the standards by producing poor-quality products – as long as it was done consistently. ISO 9000:2000 was a response to the broad dissatisfaction that resulted from the old standards. (Evans, Lindsay 2008)

The latest version of ISO 9004 is from the year 2009 and the latest ISO 19011 from 2011. The newest version of ISO 9000 and ISO 9001 was released in September 2015. The newest version of ISO 9001 aims to reflect the changed global situation. Trade has become increasingly more global as trading across borders is easier. Economies are growing more towards service based economies and supply chains are becoming more and more complex. The 2015 version looks beyond the contractual customer. Other parties, such as end users, consumers and regulatory bodies, are taken more into account. The focus is always in achieving conformity of products and services to meet customer needs and expectations. Risk-based thinking enhances the process approach in the 2015 version. It is about recognizing that not all processes have the same impact on the organizations ability to deliver conforming products and services. (ISO 2015)

Processes are to be managed as an interacting system and using a Plan-Do-Check-Act practice. The 2015 version has no specific prescribed documented procedures. It is left to the organization to define their own needs for documentation in order to manage the processes. The role of the standard is to form a solid and consistent base for sector standards and provide a stable set of requirements for regulators. The goal is that customers through the whole supply chain can have confidence in the products and services from the certified suppliers. ISO 9001 provides a common framework for all management system standards using a high-level structure that ensures consistency. All management objectives can be handled using the same base structure. The certification according to the 2008 standards is valid until September 2018. (ISO 2015)

3.4.4 Six Sigma

Six Sigma is a business improvement approach which has gained a significant amount of credibility especially because large prosperous companies have adopted the concept. The term Six Sigma is based on a statistical measure that equates 3.4 or fewer errors or defects per million opportunities. The ultimate goal of Six Sigma is that the organization has all critical processes at a Six Sigma level of capability. The aim is in seeking to find and eliminate causes of defects and errors in manufacturing and service processes. This is done by focusing on outputs that are critical to customers and a clear financial return for the organization. The concept is facilitated through the use of quality improvement and control tools by teams whose members are trained to provide fact-based decision-making information. Six Sigma concentrates on measuring product quality and driving process improvement and cost savings throughout the organization. (Evans, Lindsay 2008)

The pioneer of the Six Sigma concept was Motorola. However, the recognized benchmark for Six Sigma implementation is General Electric. Six Sigma has become a vital part of GE's company culture. As GE continues to acquire new companies, integrating Six Sigma into different business cultures is a notable challenge. Six Sigma is a priority in acquisitions and is addressed early in the acquisition process. (Evans, Lindsay 2008)

Six Sigma as a quality framework is something more than just a duplicated version of the older quality approaches, such as Total Quality Management. Six Sigma considers many human issues: management leadership, a sense of urgency, focus on results and customers, team processes and culture change. The process issues addressed by Six Sigma include the use of process management techniques, analysis of variation and statistical methods, a disciplined problem solving approach, and management by fact. Six Sigma has elevated especially the importance of statistics and statistical thinking in quality improvement. The focus on measurable bottom-line results, a disciplined, statistical approach to problem solving, rapid project completion and organizational infrastructure make Six Sigma an effective methodology for improvement. Some distinct differences in the approaches of TQM and Six Sigma are presented in table 3. (Evans, Lindsay 2008)

Table 3 Key differences between the approaches of Total Quality Management and Six Sigma. (Evans, Lindsay 2008)

Total Quality Management	Six Sigma
Based highly on worker empowerment and teams	Is owed by business leader champions
Activities generally occur within a function, process or individual workplace	Projects are genuinely cross-functional
Training is often limited to simple improvement tools and concepts	Focus on more advanced statistical methods and a structured problem-solving methodology
Focused on improvement with little financial accountability	Requires a verifiable return on investment and a focus on the bottom the bottom line

Six Sigma companies train their managers and supervisors to be competent process improvement experts. The Six Sigma Plus expert level of Green Belt is usually conferred on workers who, besides their basic assignments, apply Six Sigma principles. Black Belts guide projects with Six Sigma practices. They can be seen to work as Six Sigma project managers above the Green Belts. Higher in the hierarchy are the Master Black Belts and the Champions. Champions implement Six Sigma principles over the whole company. Master Black Belts collaborate with the Champions, work using the statistical tools and establish Six Sigma throughout all organization sectors. Green Belts and Black Belts are guided by the Master Black Belts. Six Sigma is also about dealing with organizational resistance. The managers are trained in overcoming resistance to change. (Smith et al. 2002)

4 Standardization and Threads

A standard is a uniform solution that is prepared and approved in a specific way. It is aimed for repeated application and strives to ensure the safety and compatibility of a device or an activity. (Lakervi, Partanen 2008) Standardization covers for example threads, screws, nuts, voltages, protective relays and gas cylinder valves (Pere 2009). Legislation is simplified as only the relevant requirements are listed and details are determined in the standards. Design, communication and international trade become easier and costs are decreased as a result of standards. Standards often include quality requirements in some form. Standards are used in certifications to make sure the results are unbiased and comparable. Standards compile plenty of technical information and useful solutions. (Lakervi, Partanen 2008) Standards define notations, ways for expressing matters, variables and units. The intent is to create procedures which are in compliance with the requirements. This goal applies to all fields of operations. (ISO 1998a) In this chapter standardization is discussed from the point of view of standardization organizations and standardization of threads. In addition to the ISO 965 general purpose metric threads the chapter presents other relevant thread types. Lastly, the chapter deals with screw mechanics and the effect of thread pitch.

4.1 Organizations for Standardization

This chapter represents how standardization is managed in international or continental parent organizations. The members of the parent organizations are usually national standardization organizations which perform the tasks related to standardization within their field of operation.

4.1.1 International Scale

The International Organization for Standardization (ISO), founded in 1947, is a worldwide federation of national standard bodies (ISO member bodies). The work of preparing international standards is usually carried out through ISO technical committees (TC). (ISO 1998a) Technical committees can be divided into subcommittees which may have separate working groups. The ISO technical committees have in total about 500 subcommittees which also have around 500 working groups. (Pere 2009) Standards are prepared openly. A draft of a standard is usually prepared by a team consisting of experts interested in the matter at stake. For the most part, the experts represent the industry, a research institute or authorities. (Lakervi, Partanen 2008) Each member body interested in a subject matter has the right to be represented on that committee (ISO 1998a). The standard proposals go through a circulation of for comment multiple times if need be. The final proposal is approved by voting. The standards are prepared as a European and international cooperation. (Lakervi, Partanen 2008)

The International Electrotechnical Commission (IEC) was founded in 1906 for managing the standardization of the electrical and electronics industry (Lakervi, Partanen 2008). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields (IEC 2003). IEC publishes standards concerning the electrical and electronics industry and the IEC standards are the basis for the national regulations and standards in more than 100 countries. International Telecommunication Union (ITU) is responsible for the international standardization concerning television. (Lakervi, Partanen 2008)

4.1.2 European Scale

European Committee for Standardization (CEN), founded in 1961, is an association that links together the national standardization bodies of 33 European countries. Each European standard is recognized across the whole Europe and automatically becomes the national standard in 33 European countries. (CEN 2015) The European Committee for Electrotechnical Standardization (CENELEC), founded in 1973, is responsible for European standardization in the area of electrical industry. CENELEC defines the European EN standards and the harmonization documents (HD). CENELEC works in close cooperation with IEC and the standards are largely based on IEC standards. EN standards must be published identical in all of the member states of CENELEC. Diverging national standards are not allowed. The harmonization documents must be taken into consideration when composing a national standard in a field not covered by an EN standard. The aim of EN standards is to guarantee the single market within the European Union (EU) and European Free Trade Association (EFTA). (Lakervi, Partanen 2008)

Within the European Union, EU directives set common demands that have to be enacted in the legislation of every member state. New approach directives are used when dealing with technical safety. New approach directives only specify the essential requirements. The technical solutions for meeting the requirements are presented in the corresponding European standards. Standards are not fully binding. A product may somehow deviate from the standard. In this case, the manufacturer must prove that the product fulfils the essential requirements set in the directive. Proving this without complying with the standard may be immensely burdensome. A product meeting the requirements can be sold throughout the European single market. The product can also be given a Certified Equipment (CE) marking. By using the CE marking the manufacturer or the importer guarantees the product meets the set requirements. (Lakervi, Partanen 2008)

The central directives in the electrical industry include the European Commission low voltage directive (2006/95/EC), the electromagnetic compatibility (EMC) directive, the ATEX directive for explosive atmospheres and the machinery directive (2006/42/EC) which covers also the electrical devices of machines. (Lakervi, Partanen 2008)

4.1.3 Standardization in Finland

The central organization for standardization in Finland is Suomen Standardoimisliitto SFS ry (SFS), founded in 1924. It is an independent and non-profit-making organization. Members of SFS include various organizations from industry and commerce and the Republic of Finland. The main tasks of SFS encompass formulating and approving SFS-standards, publishing and selling standards and informing. SFS is a member of ISO and the European Committee for Standardization (CEN). SFS ensures Finland has an assemblage of standards meeting the requirements of the country. (SFS 2015) National standards are enacted in Finland only if a European or an international standard concerning a particular matter does not exist (Lakervi, Partanen 2008).

In Finland the standardization of the electrical and electronics industry is taken care by SESKO ry that interacts with IEC and CENELEC. SESKO ry is a part of SFS. The generality of SFS-standards is based on or coincides with international or European standards. (SFS 2015) Nearly every new Finnish standard in the field of electrotechnology is based on CENELEC or IEC standards. The majority of EN standards is listed and approved in Finland by naming them SFS-EN. Only a few standards are published in Finnish. (Lakervi, Partanen 2008)

4.1.4 Standardization in France

The French standardization organization, AFNOR (Association Française de Normalisation), directs and coordinates the establishment of the French national standards (NF). AFNOR is the French member of European and international non-governmental standards organizations such as CEN and CENELEC in Europe, and ISO and IEC internationally. AFNOR defines itself as an international services delivery network that revolves around 4 core competency areas: standardization, certification, industry press, and training. AFNOR Competencies provides training in management systems, system methods and audit methods in total for approximately 10,000 persons annually. (AFNOR 2015)

4.1.5 Factory Standards

Industrial plants may need to draw up new standards relating to topics which are not covered by any national or industry standard. Tooling allowances and drafts in moulding are typical examples of the matters at stake. Companies draw up factory standards based on the specific manufacturing methods and equipment. Factory standards have a noteworthy effect on manufacturing, storage, purchasing and the design work. Design costs are lowered as the components and equipment are standardized. Manufacturing costs are lowered because of larger batches and lower tool costs. If factory standards limit the types and dimensions of the articles in storage, capital and storage space is saved. Also the acquired batches can become larger and the cost per unit is decreased. Tool and model costs are reduced when fewer sizes and shapes are used. (Pere 2009)

4.2 Thread Standards

Covering thread standards in more detail is relevant in the scope of this thesis. The establishment of thread standards is first presented concisely. Then the designation and tolerances of threads are covered. Lastly, thread types that are different to the metric ISO thread are dealt with.

4.2.1 Establishment of Thread Standards

ISO Technical Committee ISO/TC 2 Fasteners is in a position to dispose of an almost complete system of ISO standards on fasteners. The system uses ISO standards on threads prepared by ISO Technical Committee ISO/TC 1 Screw Threads. The system comprises standards for the most commonly used fasteners for general applications including the necessary standards for tolerances, mechanical and functional properties and testing. It also comprises standards on terminology, designation, marking and acceptance and other necessary basic standards. (ISO 2015)

4.2.2 Designation of Threads

The designation of general purpose metric threads is dictated in the ISO 965 standard. The ISO 965 standard consists of the following 5 parts, under the general title ISO general purpose metric screw threads — Tolerances:

1. Principles and basic data
2. Limits of sizes for general purpose bolt and nut threads – Medium quality
3. Deviations for constructional screw threads
4. Limits of sizes for hot-dip galvanized external threads to mate with internal threads tapped with tolerance position H or G after galvanizing
5. Limits of sizes for internal screw threads to mate with hot-dip galvanized external screw threads with maximum size of tolerance position h before galvanizing (ISO 1998b)

The complete designation for a screw thread comprises a designation for the thread system and size, a designation for the thread tolerance class followed by further individual items if necessary. According to the requirements of ISO 68-1, ISO 261, ISO 262, ISO 724, ISO 965-2 and ISO 965-3 general purpose metric screw threads shall be designated by the letter M followed by the value of the nominal diameter and of the pitch, expressed in millimetres and separated by the sign "x". An example of this notation is M8 x 1.25. (ISO 1998b)

The class designation for tolerances comprises two elements: a class designation for the pitch diameter tolerance followed by a class designation for the crest diameter tolerance. Each tolerance designation consists of two things: a figure indicating the tolerance grade and a letter indicating the tolerance position. Capital letters are used for internal threads and small for external threads. If both the pitch diameter class designation and crest diameter class designation are the same it is not necessary to repeat the symbols. The same applies to major or minor diameter for internal and external threads respectively. Principally the absence of tolerance class designation means that the specified tolerance quality is medium. In internal thread classes this applies to class 5H for threads up to and including M1.4 and class 6H for threads M1.6 and larger. Threads with pitch P = 0.2 mm deviate from this since the only defined tolerance grade for those is 4. The absence of tolerance class designation for external threads means medium tolerance quality with the following tolerance classes: 6h for threads up to and including M1.4 and 6g for threads M1.6 and larger. (ISO 1998b)

A number of tolerance grades have been established for pitch diameter and crest diameter. In each case, grade 6 shall be used for tolerance quality medium and normal length of thread engagement. The grades below 6 are intended for tolerance quality fine or short length of thread engagement or for both. The grades above 6 are intended for tolerance quality coarse or long lengths of thread engagement or for both. In some grades, certain tolerance values for small pitches are not shown because of insufficient thread overlap or the requirement that the pitch diameter tolerance shall not exceed the crest diameter tolerance. (ISO 1998b)

The designation for the group of length of thread engagement S for short and L for long should be added to the tolerance class designation separated by a dash. The absence of the designation for the group of length of thread engagement means the specified group is N, standing for normal. A fit between two threaded parts is indicated by the internal thread tolerance class followed by the external thread tolerance class separated by a stroke. (ISO 1998b)

The example notation M20 x 2 – 5H – S stands for a metric internal thread with the nominal diameter of 20 mm and a pitch of 2 mm. The tolerance class for both the pitch and minor diameter is 5H and the designation for the group of length of thread engagement is S (short). The example notation M20 x 2 – 6H/5g6g represents a similar nominal thread but also the fit between threaded parts is expressed in the notation. The tolerance class for both the pitch and minor diameter of the internal thread is 6H. 5g defines the pitch tolerance class and 6g the major diameter tolerance for the external thread. Since the designation for the group of length of thread engagement is not shown it means the group N (normal) is specified. (ISO 1998b)

The ISO 965 standard defines also the designation of multiple-start screw threads as well as left hand threads. Multiple-start metric screw threads are designated by the letter M followed by the value of the nominal diameter, the sign x, the letters Ph and the value of the lead, the letter P and the value of the pitch, a dash, and the tolerance class. The letters LH in the designation of a thread specify that a left hand thread is in question. The marking is separated by a dash as in the following example: M8 x 1 – LH. Additionally the tolerance defines the correct shape of the root contours of threads. (ISO 1998b)

4.2.3 Recommended Tolerances

Certain tolerance positions are standardized. For internal threads these are G with positive fundamental deviation and H with zero fundamental deviation. For external threads e, f and g with negative fundamental deviation and h with zero fundamental deviation are the standardized tolerance positions. The preferred tolerance classes are shown in tables 4 and 5. Tolerance classes in bold print are the first choice. Tolerance classes in ordinary print are the second choice. Tolerance classes in parentheses are the third choice. These classes are recommended in order to reduce the number of gauges and tools needed. (ISO 1998b)

For coated threads, the tolerances in tables 4 and 5 apply to the parts before coating, unless otherwise stated. After coating, the actual thread profile should not at any point transgress the maximum material limits for positions H or h. (ISO 1998b)

Table 4 The recommended tolerance classes for internal threads. The primary options are bolded, secondary are in ordinary print and the least favourable are in parentheses. (ISO 1998b)

Tolerance quality	**Tolerance position G**			**Tolerance position H**		
	S	N	L	S	N	L
fine	–	–	–	4H	5H	6H
medium	(5G)	**6G**	(7G)	**5H**	**6H**	**7H**
coarse	–	(7G)	(8G)	–	7H	8H

Table 5 The recommended tolerance classes for external threads. The primary options are bolded, secondary are in ordinary print and the least favourable are in parentheses. (ISO 1998b)

Tolerance quality	Tolerance position e			Tolerance position f			Tolerance position g			Tolerance position h		
	S	N	L	S	N	L	S	N	L	S	N	L
fine	–	–	–	–	–	–	–	(4g)	(5g4g)	(3h4h)	**4h**	(5h4h)
medium	–	**6e**	(7e6e)	–	**6f**	–	(5g6g)	**6g**	(7g6g)	(5h6h)	6h	(7h6h)
coarse	–	(8e)	(9e8e)	–	–	–	–	8g	(9g8g)	–	–	–

Group N is recommended if the actual length of thread engagement is unknown as it is in the manufacturing of standard bolts. Commercial external and internal threads rely on tolerance classes within broad frames. The following general rules can be applied for choosing a suitable tolerance quality:

- Fine: for precisions threads, when little variation of fit character is needed.
- Medium: for general use and unknown length of thread engagement.
- Coarse: for cases where manufacturing difficulties can arise, for example when threading hot-rolled bars and long blind holes. (ISO 1998b)

All of the recommended tolerance classes for internal threads can be used in conjunction with any of the recommended tolerance classes for external threads. However, for guaranteeing adequate overlap, the finished components should preferably utilize the fits H/g, H/h or G/h. (ISO 1998b)

4.3 Screw Mechanics

The chapter first explains the formation of threads through the concept of screw line. Then the meaning and significance of the thread profile is construed. Different uses for different thread profiles are presented.

4.3.1 Screw Line

A screw line is a helical curve. It is formed as a point moves along a cylindrical surface at a constant angular velocity compared to the axis of the cylinder. Simultaneously the point moves at a constant speed parallel to the axis of the cylinder. (Airila, Ekman et al. 2010)

The pitch of a thread is the change of the z coordinate when a full rotation of 2π is travelled around the helical screw line. In other words, pitch equals the travel of a screw along its longitudinal axis when the screw is rotated one revolution compared to the internal thread acting as the counterpart. The angle of thread can be calculated as shown in formula 1. (Airila, Ekman et al. 2010)

$$\gamma = arctan \frac{P}{\pi d_s} \qquad (1)$$

Where d_s is the diameter of the cylinder, P is the pitch of the thread and γ is the angle of thread. (Airila, Ekman et al. 2010)

4.3.2 Thread Profiles

The most important surface of a screw is the surface of the thread. The surface of the thread is formed as a suitable thread profile travels along the screw line. The envelope of the thread profile forms the thread. The essential design parameters of the thread profile are the pitch, the flank angle, the height of the profile triangle, the truncation of the profile crest and the corner radius of the root profile. (Airila, Ekman et al. 2010)

The most commonly used thread profiles include sharp threads, trapezoidal threads and rounded threads. Standardization of threads has been an ongoing process for over a hundred years. The goal is to achieve interchangeability, reliability and cost-effectiveness in production. The different systems of measures in different countries make standardization complicated. (Airila, Ekman et al. 2010)

A sharp thread is the most common thread profile. The profile is formed by an isosceles triangle that has a truncated crest. The popularity of the profile is based most of all on the following matters:

- Manufacturing is easy both by cutting and cold forming.
- The radial and the axial clearance can be controlled by moving the profile along the radius of the screw.
- The deformations caused by forces along the radius of the screw help balancing the forces between the threads.
- The high friction caused by the sharp flank angle is beneficial from the perspective of fastening screws that are meant to hold things in place. (Airila, Ekman et al. 2010)

Fastening screws are mainly used for connecting mechanical components or other structural elements. Lead screws are meant for converting rotational motion into liner movement or vice versa. The difference between fastening and lead screws is not always explicit. Sometimes fastening screws are used for positioning and lead screws may occasionally be used for holding a component stationary. (Airila, Ekman et al. 2010) Purposes of using screws are listed in table 6.

Table 6 Different purposes of using a screw. (Airila, Ekman et al. 2010)

Purpose of use	Example
Actual fastening screw	Fastening the bicycle wheel axle to the frame
Tightening screw	Tightening the bicycle seat in place
Blanking plug	Fuel tank cap
Positioning screw	Adjustment of a flagpole
Amplifying force	Car jack
Differential screw	Precise focusing of a microscope
Amplifying movement	Extending the measuring scale of a microscope
Actual lead screw	Lead screw of a lathe

Screw connections are generally easy to install and to disassemble. It is a reliable method when used correctly. Screw connections can be used in very diverse circumstances. The drawbacks of screws include that they have multiple points of discontinuity which causes local stress. Also, the reliability of a screw connection rests highly upon the tightening torque that can be difficult to control. (Airila, Ekman et al. 2010)

Lead screw profiles have to meet two basic requirements: controlling free play should be straightforward and the flank angle has to be acute in order to minimise friction. The trapezoidal thread meets these requirements adequately. A trapezoidal thread is also easier to manufacture than a flat thread that has a rectangular thread profile. A buttress thread is an excellent solution for lead screws that experience the largest loading always in the same direction. The angle of the thread profile on the side that carries the load is small. This gives the buttress thread lower friction compared to the trapezoidal thread. Nevertheless, the base of the thread profile is thick enough for carrying high loads. (Airila, Ekman et al. 2010)

4.4 Separate Thread Standards

The International System of Units (SI), also called the metric system, is used in virtually all countries around the world. Globally a few thread types are clearly the most commonly used: certain varieties of metric threads and of unified national threads which are defined in inches. (Abdo 2011)

In Finland the most typically used thread types include the coarse metric ISO thread, the metric ISO fine thread, the metric ISO trapezoidal thread, pipe threads, UNC (Unified National Coarse) ISO threads and UNF (Unified National Fine) ISO threads. UNC and UNF ISO threads are mainly used in countries utilizing either imperial units or the United States customary system. Due to component sizing and spare parts originating from these countries, the system must be recognized also elsewhere. (Pere 2009)

This thesis mainly discusses metric threads in accordance with the ISO 965 standard. This chapter covers some other essential thread types that are relatively commonly used in a global perspective.

4.4.1 UN Threads

The United States Customary system requires some basic knowledge concerning certain combinations of numbers. The unit one inch can be divided into equal units, as in halves (1/2”), quarters (1/4”) or eights (1/8”) of an inch. Sizes of fasteners, tools and parts are stated in inches or parts of inches. The parts of inches are expressed either as fractions or as decimal numbers. A fastener diameter of half an inch can be written as ½” or as a decimal number 0.5” and a fastener diameter of 1/8” would be 0.125” as a decimal number. Figure 7 displays the bolt dimensioning of the United States Customary System and the International System of Units. The units of measurement differ and so does the definition of pitch. (Abdo 2011)

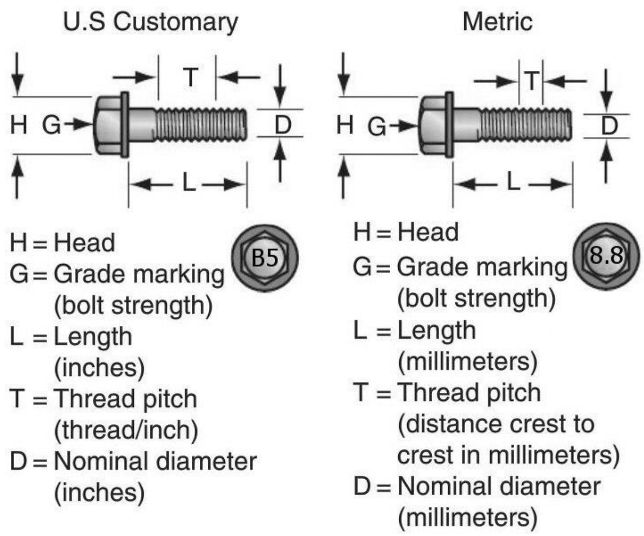

Figure 7 The critical bolt dimensions in the United States Customary System and the International System of Units (SI), in other words, the metric system. (Abdo 2011)

4.4.2 Piping Threads

There are standardized thread profiles for connecting piping and the related coupling elements. ISO pipe threads have two different operating principles:

- Pipe threads that utilize the threads for forming pressure-sealed connections defined in ISO 7/1
- Pipe threads where the threads do not for a pressure-sealed connection defined in ISO 228/1 (Airila, Ekman et al. 2010)

Commonly used threads in the United States Customary System include the tapered piping thread (PT) and the parallel piping thread (PF) (Abdo 2011). In tapered piping threads the seal is formed on the threads. Parallel piping threads only hold the components together and a separate mechanism is needed for forming the seal.

Also the Whitworth threads that originate in the United Kingdom are a notable piping thread type. In Whitworth threads the sealing is done on the threads defined in the DIN (Deutsches Institut für Normung) 2999 standard (Hahnreiter Gewindetechnik 2014).

4.4.3 Rounded Threads

Rounded thread is a thread type that is not very sensitive to knocks or dirt. Therefore a rounded thread in accordance with the DIN 405 standard is sometimes used in fittings and in railway carriage couplings. Rounded threads are also used in electrotechnics in light bulb sockets and fuses that use a DIN 40400 thread. (Airila, Ekman et al. 2010) A light bulb thread is seen in figure 8.

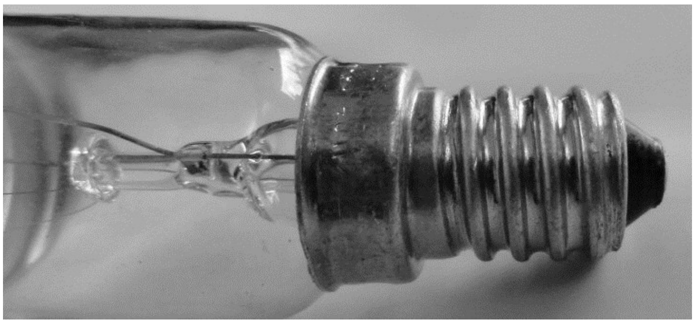

Figure 8 Light bulb sockets use a standardized rounded thread type.

4.5 Coarse or Fine Pitch Thread

The ratio between the pitch and the nominal diameter of a thread can have an influence on the endurance limit of a screw (Airila, Ekman et al. 2010). It is not in the scope of this thesis to test the effect of the thread pitch to the operation and endurance of a thread connection. This chapter discusses the topic through previous research regarding the subject.

The metric ISO threads consist of two basic alternatives: the standard coarse thread and the fine pitch thread. The coarse thread is slightly more fatigue resistant than the fine pitch thread. As anticipated the standard coarse thread is the primary choice for fastening screws. It should be used if there is no obvious reason for choosing differently. The fine pitch thread is used in the following special cases:

- The structure is thin-walled.
- A positioning screw requires a high gear ratio.
- The effective length of the screw is forced to remain short for example because of space limitations. (Airila, Ekman et al. 2010)

A fine pitch thread is a slightly better option for low strength materials (screw strength class 4.6). For hard screws (8.8 and 12.9), however, a fine pitch marginally weakens the fatigue resistance. Generally a thread with a normal pitch is the best solution for the most commonly used screw strengths (class 8.8 or harder) in the mechanical industry. (Airila, Ekman et al. 2010)

The highest stress concentration occurs in the root of the first thread. The largest portion of the total load in the engagement between an internal and an external thread is carried by the first thread. This contact load produces a bending stress in the root of the threads along with an axial load that produces tension in the bolt core. Both the bending and the axial stress contribute to the stress concentration. (Majzoobi, Farrahi et al. 2005) Internal and external threads that are touching each other can be damaged in the following two ways:

- The internal thread shears off when the internal thread is weaker than the external thread.
- The external thread shears off when the external thread is weaker than the internal thread. (Airila, Ekman et al. 2010)

Majzoobi, Farrahi et al. (2005) have conducted experimental analysis to evaluate the effect of thread pitch on the fatigue life of steel bolts. Experiments were conducted with metric ISO bolts in the nominal diameter range of 10 to 24 mm and with American Unified bolts in the range of 7/16” to 1”. The examined bolts included two variations of each nominal diameter: a variation having a standard coarse thread and a variation having a fine pitch thread. The fatigue tests were conducted using a purpose built measuring device that exposed bolts to different types of sinusoidal cycling loading. The bolts screwed to nuts. The number of cycles corresponding to the failure of some component in the thread connection was recorded as the fatigue life of the bolt connection. The mean value of multiple tests was used as the comparison value.

The experimental tests indicated that in general the fatigue life decreased as the threads nominal size increased. This applied to both the metric ISO threads and the Unified bolts. There was one slight exception: the 1” unified bolt had a slightly increased fatigue life compared to the preceding smaller 7/8” bolt. (Majzoobi, Farrahi et al. 2005)

Coarse threaded ISO bolts were always superior to fine threaded bolts in the tests. It made no difference whether the comparison between the pitches was done based on the nominal diameter or the core diameter. For unified bolts coarse threads were also superior compared to the fine threaded bolts when looking at the core stress-fatigue life curves of the results. The superiority was not as clear as it was in the tests with metric ISO bolts. The nominal stress-fatigue life curves indicate that both thread pitches have substantially the same loading capacity or fatigue strength. (Majzoobi, Farrahi et al. 2005)

The examinations performed by Majzoobi, Farrahi et al. (2005) observed four fracture mechanisms in the bolt-nut connections. The most common failure type covered nearly 70 percent of the failures. This failure occurred in the first engaging thread between the bolt and the internal thread. This is the point subjected to the maximum overall stress as mentioned earlier. The rest of the failures in the tests were covered by the bolt head shearing of (12 %), failure at the first thread immediately after the unthreaded part of the bolt (16 %) and threads of the nut shearing off completely (3 %). (Majzoobi, Farrahi et al. 2005)

Majzoobi, Farrahi et al. (2005) conclude that, on the basis of equal load and equal stress, coarse threaded ISO steel bolts are superior to fine threaded bolts within the range they tested. Coarse threaded American Unified bolts are superior to fine ones within the range tested when the comparison is done based on equal stress. When the comparison was done based on equal load and nominal diameter, no significant difference can be distinguished between coarse and fine threaded bolts.

Earlier Dragoni (1997) has examined the effect of thread pitch on the fatigue strength of ISO steel bolts fitted with standard nuts. Dragoni explains the load capacity of the bolt is related to a comprehensive notch factor which includes both stress concentration and notch sensitivity dependencies. Dragoni’s work is based on means of boundary element analyses.

The notch factor is examined as a function of nominal diameter and thread pitch for a selection of steel grades. The research expresses that the endurance load slightly increases as the pitch is decreased for small bolts of low-grade steel. Conversely, the endurance load clearly increases with the pitch for large bolts of high-grade steel. (Dragoni 1997)

Majzoobi, Farrahi et al. (2005) mention that different manufacturing techniques may have considerable effects on the fatigue behaviour of bolts of different standards. This is noted also by many others. The fatigue strength of screw threads produced by rolling is considerably higher than those produced by cutting or grinding (Forrest 1970). The same is specified also by the ASM Handbook, Volume 19, Fatigue and Fracture (1996). A comparison between the fatigue strength of rolled and machined threads is shown in figure 9.

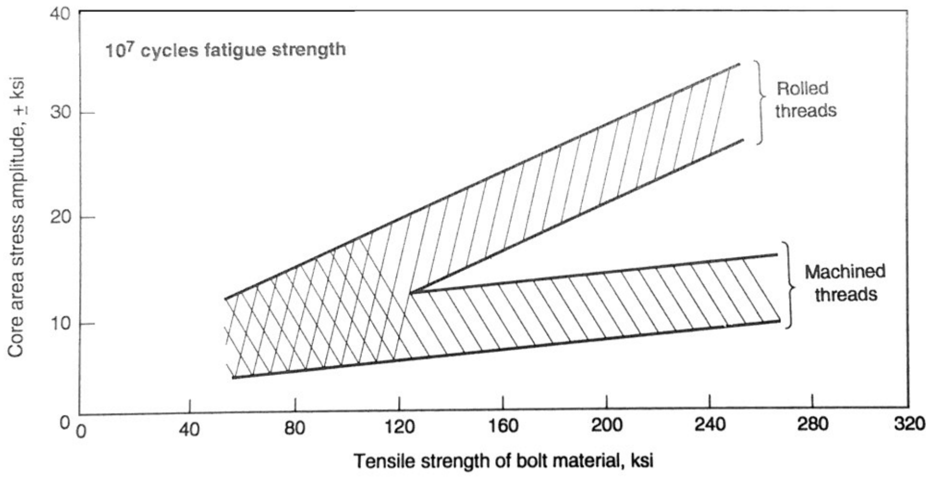

Figure 9 Axial fatigue strength at 10^7 cycles for rolled and machined bolts fitted with a standard nut. The unit ksi stands for kiloponds per square inch that is equivalent to 6.895×10^6 Pa. (ASM handbook 1996)

As a conclusion it can be stated that the pitch may have significance for the endurance of a screw connection in many applications. The research cited above was done on steel fasteners as they are a typical selection for engineering applications. The thread type and the material properties affect the situation greatly. Also the manufacturing method of the threads may have a substantial effect on the operation of a thread. Taking the foregoing into account, an all-encompassing mathematical model or examination concerning the endurance of a thread coupling can often be nearly unattainable. For the most part, defining the best solution has to be done case-specifically. Performing tests with the actual components with correct materials appears to be an effective way for performing this examination.

5 Calculations and Data Processing

This chapter presents the formulas for the calculations in this thesis. The methods for expressing the central tendency and dispersion of the data are introduced. Calculations are also stated for defining the required number of test cycles. Formulas relating to the dependency between tightening torque and axial force are introduced. The chapter describes the calculations regarding the fit between internal and external threads. The analysis done to the test result data is also explained.

5.1 Measures for Descripting Data

Characterizing the data can be beneficial in many engineering applications. This can be done by descriptive measures which often take numerical values. The goal is to make communication and characterization of the data easier. (Ayyub, McCuen 1997) Subsequently, the relevant methods for expressing the central tendency and dispersion of the data are presented.

5.1.1 Mean

The mean value can be formally defined as the first moment measured about the origin. Mean is also known as the average of all observations on a random variable. When each of the n observations is given an equal weight, the mean for a discrete random variable is calculated using the following formula:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} \quad (2)$$

Where n equals the number of variables. (Ayyub, McCuen 1997)

5.1.2 Variance

The variance is the second moment about the mean. The units of the variance are the square of the units of the random variable. When each of the n observations in a sample is given equal weight the variance is given by:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{X})^2 \quad (3)$$

Where n equals the number of variables, x_i the variables and $\bar{X}$ their mean. (Ayyub, McCuen 1997)

5.1.3 Standard Deviation

By definition standard deviation (σ) is the square root of the variance. Standard deviation has the same units as both the underlying variable and the central tendency measures. It is a useful descriptor of the dispersion or spread of a sample data. (Ayyub, McCuen 1997) After computing the mean values the variance and standard deviation of each test series was calculated using the following formula:

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{X})^2} \quad (4)$$

Where σ^2 equals the variance, n the number of variables, x_i the variables and $\bar{X}$ their mean. (Ayyub, McCuen 1997)

5.1.4 Histogram

Histograms and frequency diagrams are special types of charts that are commonly used to display and describe data. They are developed from the data for certain variables of interest. A histogram is a plot of the number of the data points versus selected intervals or values of a parameter. The number of intervals (k) can be subjectively selected depending on the sample size (n). The number of intervals can also be approximately determined as:

$$k = 1 + 3.3\, log_{10}(n) \quad (5)$$

Where n equals the number of variables. (Ayyub, McCuen 1997)

5.2 Determining the Required Number of Test Cycles

A statistical analysis often starts from the selection of a sample size. The selection of the sample size should be based on a clearly stated objective. (Ayyub, McCuen 1997) The objective of the sample size selection was to conclude the number of test cycles required for comparing the torque-force ration in different screw connections. The calculations are executed based on a pre-test that made it possible to identify the variance in the used test procedure.

5.2.1 Power

Power is the fraction of experiments that is expected to yield a statistically significant probability value. High power denotes a high chance that the experiment will find a statistically significant result. Power is the probability of rejecting the null hypothesis when it is false. The variable beta (β) is defined to equal 1.0 minus power. In other words β is the probability of committing a type II error which represents not rejecting a false null hypothesis. Equally the power of a test is 1 - β, since rejecting the false null hypothesis is the goal. (Giesbrecht, Gumpertz 2004)

5.2.2 Confidence Level

The level of significance (α) equals the probability of committing a type I error which is the same as the willingness of rejecting a true null hypothesis. (Giesbrecht, Gumpertz 2004) The conclusion is correct in 100 x (1 – α) % of the cases. That is to say, the conclusion is incorrect in 100 x α % of the cases. For a normal distribution the useful value for the calculations is α/2 as the confidence interval is two-sided. (Ayyub, McCuen 1997)

5.2.3 Confidence Interval for the Mean

It is of interest to notice that the confidence interval is a function of the level of confidence, the theoretical sampling distribution and the sampling characteristics. In computing confidence intervals, the choice of test statistic depends on whether or not the standard deviation of the population is known. The theorem for the case where the standard deviation is known specifies a Z statistic. Z is the critical value of the Normal distribution corresponding to a specific number. (Ayyub, McCuen 1997) The Z statistic values are read from the statistical table of the Normal distribution. In this context the relevant values for Z were $Z_{\alpha/2}$ at α/2 and Z_β at β.

For a two-sided confidence interval (μ):

The lower limit is:

$$\mu \geq \bar{X} - Z_{\frac{\alpha}{2}}\left(\frac{\sigma}{\sqrt{n}}\right) \quad (6)$$

Where X equals the mean, σ the standard deviation, n the number of variables and $Z_{\alpha/2}$ the statistic value of the Normal distribution at α/2. (Ayyub, McCuen 1997)

And the upper limit is:

$$\mu \leq \bar{X} + Z_{\frac{\alpha}{2}}\left(\frac{\sigma}{\sqrt{n}}\right) \quad (7)$$

Where X equals the mean, σ the standard deviation, n the number of variables and Zα/2 the statistic value of the Normal distribution at α/2. (Ayyub, McCuen 1997)

The width of the confidence interval increases as the confidence level is increased. It is worth acknowledging that the possibility of an incorrect conclusion cannot be totally eliminated unless the confidence interval is made exceedingly wide. This, however, means that no useful information concerning the true value can be gained. Again it can be thought that increasing the width of the confidence interval is the price that must be paid for increasing the level of confidence. (Ayyub, McCuen 1997)

5.2.4 Required Sample Size

The target of the calculations is defining a sample size that provides a reliable basis for comparing screw connections with different tolerances. A sample size of n specimens is needed for detecting a difference between the means of two samples:

$$n = \left(Z_{\alpha/2} + Z_\beta\right)^2 \frac{2\sigma^2}{u^2} \quad (8)$$

Where $Z_{\alpha/2}$ is the critical value of the Normal distribution at α/2, Z_β is the critical value of the Normal distribution at β, σ^2 is the population variance and u is the minimum difference that needs to be detected. (Select 2016)

5.3 Dependency between Tightening Torque and Axial Force

The correlation between the tightening torque and the axial force is often very relevant in applications utilizing screws or nuts (Airila, Ekman et al. 2010). This is the case also with the screw connection of an underground cable connector. The following calculations address the significance of the thread characteristics and friction for the axial force during the rotation of a screw or a nut.

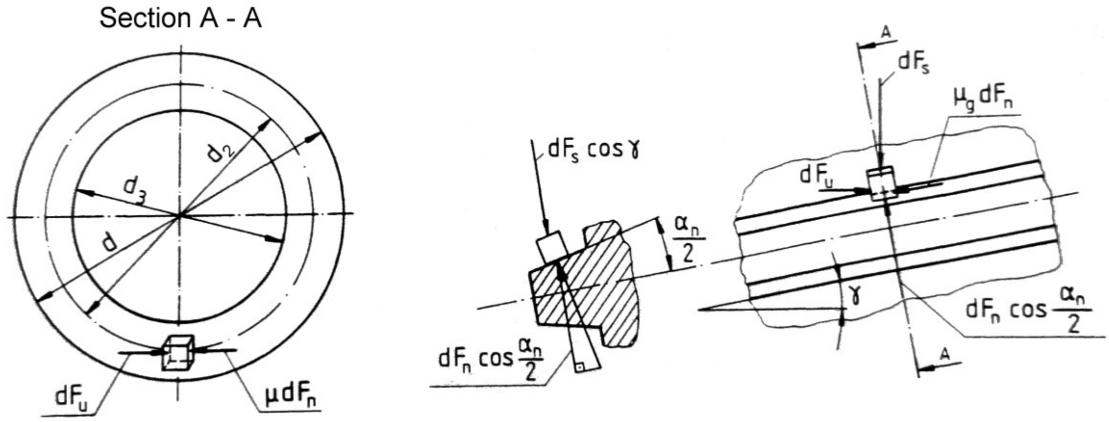

Figure 10 The forces affecting a differential element of a thread. F_u is the tangential force, F_n is the normal force, F_s is the axial force and μ_g is the coefficient of friction in the thread, α_n is the flank angle, γ is the angle of thread, d is the major diameter of the thread, d_2 is the pitch diameter and d_3 is the minor diameter. (Airila, Ekman et al. 2010)

In most cases the flank angle of the thread is larger than zero. In these cases the tightening torque can be defined based on the situation in figure 10. The balance equations in the tangential and axial directions are as follows:

$$dF_u - \mu_g\, dF_n \cos\gamma - dF_n \cos\frac{\alpha_n}{2} \sin\gamma = 0 \quad (9)$$

$$dF_s + \mu_g\, dF_n \sin\gamma - dF_n \cos\frac{\alpha_n}{2} \cos\gamma = 0 \quad (10)$$

Where F_u is the tangential force, F_n is the normal force, F_s is the axial force, μ_g is the coefficient of friction in the thread α_n is the flank angle and γ is the angle of thread. (Airila, Ekman et al. 2010)

The same can be rearranged to (Airila, Ekman et al. 2010):

$$dF_u = (\mu_g \cos\gamma + \cos\frac{\alpha_n}{2} \sin\gamma) dF_n \quad (11)$$

$$dF_s = (-\mu_g \sin\gamma + \cos\frac{\alpha_n}{2} \cos\gamma) dF_n \quad (12)$$

Now the equations can be used for solving the tangential force (Airila, Ekman et al. 2010):

$$dF_u = \frac{\mu_g \cos\gamma + \cos\frac{\alpha_n}{2} \sin\gamma}{-\mu_g \sin\gamma + \cos\frac{\alpha_n}{2} \cos\gamma}\, dF_s \quad (13)$$

The torque (M_g) needed for moving a single point in a thread is:

$$dM_g = \frac{1}{2} d_2 dF_u \tag{14}$$

Where d_2 is the pitch diameter and Fu is the tangential force (Airila, Ekman et al. 2010).

Equation 13 can be substituted into equation 14 (Airila, Ekman et al. 2010):

$$dM_g = \frac{d_2}{2} \frac{\mu_g \cos\gamma + \cos\frac{\alpha_n}{2} \sin\gamma}{-\mu_g \sin\gamma + \cos\frac{\alpha_n}{2} \cos\gamma} \, dF_s \tag{15}$$

In practice, the coefficient of friction, the pitch angle and the flank angle are constants that do not depend on the forces acting in the screw connection. Thus equation 15 can be integrated to form the equation for the tightening torque of a nut or a screw (Airila, Ekman et al. 2010):

$$M_g = \frac{d_2}{2} \frac{\mu_g \cos\frac{\alpha_n}{2} \tan\gamma}{-\mu_g \tan\gamma + \cos\frac{\alpha_n}{2}} \, F_s \tag{16}$$

Equation 16 can be further simplified when typical threads with a triangular thread profile and a large flank angle are at stake. For example metric ISO threads have a flank angle of $\alpha_n = 60°$, in which case the following applies:

$\mu_g \tan\gamma \ll \cos\frac{\alpha_n}{2}$ (Airila, Ekman et al. 2010)

Now the equation for the tightening torque is simplified to the following form (Airila, Ekman et al. 2010):

$$M_g = \frac{d_2}{2} F_s \left(\frac{\mu_g}{\cos\frac{\alpha_n}{2}} + \tan\gamma \right) \tag{17}$$

5.4 Clearance between the Threaded Components

Calculations were conducted for determining the suitable thread tolerances for the torque-force tests. The objective was to choose pairs of internal and external threads that would be relevant for the test. The clearance in the pairs was calculated by comparing the tabular values of each tolerance. The dimensions derive from the ISO 965-1 standard for metric ISO threads. The calculations cover the base difference, major diameter, pitch diameter and minor diameter. The calculations concerning the latter three produced a minimum and maximum clearance regarding the subject value.

The maximum clearance concerning each diameter is computed by comparing the maximum value of the internal thread to the corresponding minimum value of the external thread. The minimum clearance concerning each diameter is computed by comparing the minimum value of the internal thread to the corresponding maximum value of the external thread. The chosen thread variations along with the clearances in the formed pairs are presented later in chapter 7.1.3.

5.5 Analysis of the Measurement Data

The collected data was processed and the calculations were solved using the Microsoft Excel spreadsheet. The data was converted to graphs depicting the relationship between the torque applied to the screw and the force generated at the tip of the screw. Based on the visual assessment of the graphs it was obvious that some results could be discarded as unsuccessful tests. In some cases the ratio between torque and force deviated from the vast majority of the results so clearly that these result clearly did not represent the actual situation. Examples of deviating erroneous graphs are shown in figure 11 where the force in some test runs built up very poorly. The threads also broke early. Likely reasons for the deviations were some sort of flaws in the threads or unwanted torsion formed in the test setup.

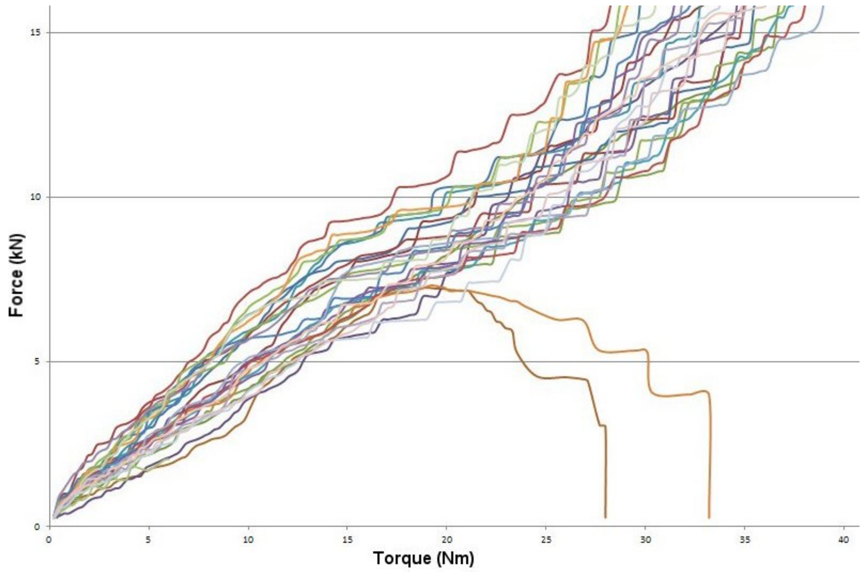

Figure 11 Some test runs clearly deviated from the majority. Two graphs stand out due to poor build-up of force. The graphs were discarded from the pre-test results because the dependency between torque and force was distinctly different compared to the vast majority of the test runs. Not only did the force build up poorly but also the thread broke exceptionally early.

The dependable graphs were fitted with a smooth polynomial trend curve. A reference value for each test run was established based on the polynomial trend curve equations. The chosen reference value was the ratio between torque and force at a certain value of torque. The unit of the reference value is kN/Nm and the symbol used for it in this thesis is R. The same unit applies to the standard deviation deduced from it. The unit for variance is now $(kN/Nm)^2$. Figure 12 demonstrates the trend curves fitted for a pair of test run graphs.

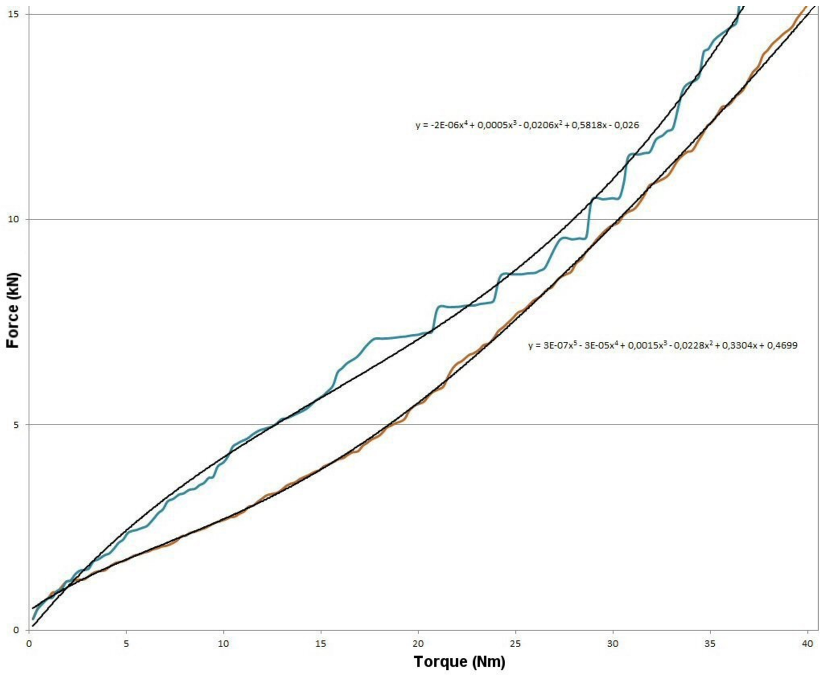

Figure 12 Polynomial trend curves shown as smooth black lines were fitted for the test result graphs. The trend curve equations were used for defining a reference value for each test run.

The graphs of the results and the distribution of the calculated reference values clearly proved that the test results follow the Normal distribution. This is the justification for using the chosen sample size selection method.

6 Testing Arrangements

Tests were performed in order to determine factors affecting the perceived mechanical quality and the overall operation of the screw coupling in the underground cable connector. An objective was to find out what is the possible effect of changing the tolerance of the screw thread. The most relevant factors in the tests were the torque needed for turning the screw and the force at the tip of the screw. In the latter part of the chapter, measures for benchmarking of relevant rival products are concerned.

6.1 Torque-Force Testing

The torque-force testing arrangement was the most significant method developed in the frameworks of the thesis. The chapter describes the testing arrangement and the measuring procedure.

6.1.1 Testing Arrangement

A testing arrangement was developed for observing the effect of different thread tolerances on the ratio between the torque applied to the screw and the force generated at the tip of the screw. A force sensor and a torque measuring device were essential components of the test equipment. The torque measuring device consisted of an electric motor used for rotating the screw and a torque sensor used for measuring the torque needed for the rotation. Since, it was impractical to try to measure the force applied to the cable inside a connector, a simplified arrangement, shown in figures 13 and 14, was constructed.

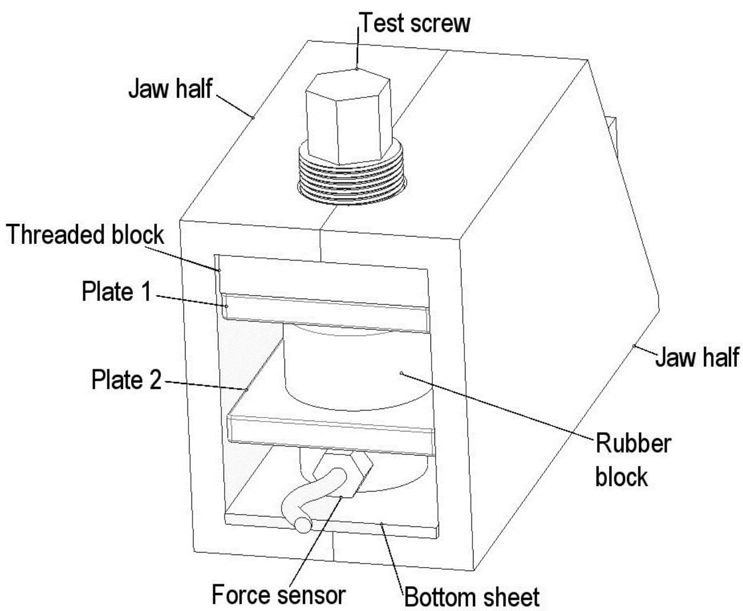

Figure 13 The testing arrangement for measuring the ratio between the torque applied to the screw and the force generated at the tip of the screw. A torque measuring device rotates the screw at a steady angular velocity and registers the required torque. The force sensor registers the generated force.

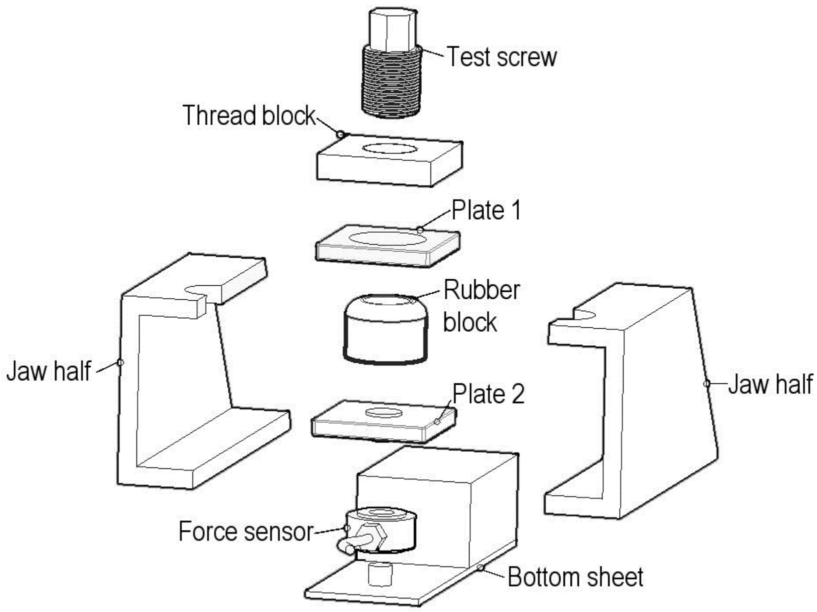

Figure 14 The testing arrangement shown in an exploded view.

The steel jaws are fastened to a vice clamp with screws. The vice can be trimmed so that the screw is directly under the torque measuring device rotating it. The rubber block is placed in the middle to offer elasticity in the assembly. It can be seen to act as a substitute for the settling of the cable inside an actual cable connector. Plates 1 and 2 are machined out of steel and they are hardened. The bottom sheet is made out of steel. The aluminium test screw has a thread that corresponds to a production screw. Screws with different tolerances are tested. The screw is highly simplified by removing all of the grooves from the thread area. The aim is to measure the effect the thread tolerance has on the torque-force ratio. The purpose of the screw design is to minimise the impact of other factors. The threaded block resembles the connector body and its internal thread. The measuring instruments that are used in the testing arrangement are presented below in table 7.

Table 7 The measuring instruments of the testing arrangement.

Instrument	Manufacturer and Model
Force sensor	Scaime K180 sensor with Lahti Precision TPL-300 digital load cell amplifier
Rotary Torque Transducer	Datum Electronics M420-S1
Servo Motor of Torque Measuring Device	Yaskawa Electric SGMGV

6.1.2 Measuring Procedure

The screw thread and the thread of the block resembling the connector body are greased for the test to allow optimal movement of the screw. Grease is applied also to the tip of the screw which is in contact with plate 1 during the test. Each screw and threaded block is used only once. A new rubber block is placed in the set-up for every run. This is to make sure that no errors are caused by the possible changes in the performance of the rubber.

During the test the screw is rotated using the torque measuring device which rotates the screw at a steady angular velocity and registers the required torque for doing this. The threaded block experiences a push upwards and stays in place pressed against the jaws. As the screw rotates it moves downwards and pushes against plate 1. Plate 1 moves down and the rubber block beneath it slowly flattens. The rubber block passes on the movement as pressure to plate 2. Plate 2 hardly moves as the compression of the force sensor beneath it is only minuscule. The compression of the force sensor causes as change in the resistance in the sensor. This is translated into a force reading that is pressing against the sensor. The test is continued until the thread breaks, the screw shears or the maximum force allowed by the force sensor is reached.

The course of the test is controlled from a computer using the LabVIEW software by National Instruments. Suitable parameters according to the measuring instruments are chosen. The torque from the torque sensor and the force from the force sensor are sent to computer software that records the data into a Microsoft Excel spreadsheet.

6.1.3 Torque-Force Pre-test

A pre-test was needed for defining the variance of the testing arrangement. The pre-test was conducted using normal production versions of the shear-head screws. Threaded blocks were manufactured for the pre-test. The testing arrangement and measuring procedure were carried out as it was explained in the preceding chapters. The pre-test results and their variance were needed for defining the sample size of the actual torque-force tests.

6.2 Benchmarking of Rival Products

As a part of the research also relevant rival products were examined for benchmarking purposes. Underground cable connectors are commonly based on the same principle in which a cable is inserted into the connector body from both ends and fastened using screws. This chapter describes the methods used for evaluating the tolerances and feel of the screw couplings. Also the thread cross-sections of split connectors were assessed based on microscopic images.

6.2.1 Tolerance Examination

The competing cable connectors were examined using micrometres and thread gauges. Ordinary external and internal micrometres were used for measuring the external major diameter and the internal minor diameter. The screws were measured using a micrometre meant for measuring the pitch diameter. A micrometre for measuring the pitch diameter of the internal threads other than M18x1 was not available. Thus the internal thread pitch diameter was measured only from the connectors having an M18x1 thread. Figures 15 and 16 illustrate the pitch diameter measurements.

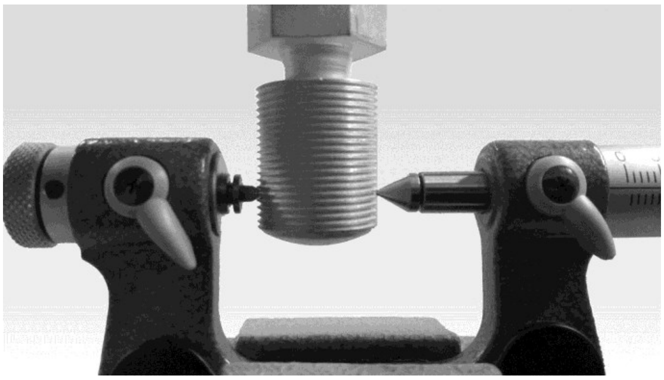

Figure 15 A micrometre for measuring the pitch diameter of external threads. The tips that brace the screw are meant for measuring screws having a specific pitch. The tips can be changed to allow the measuring of different pitch variations.

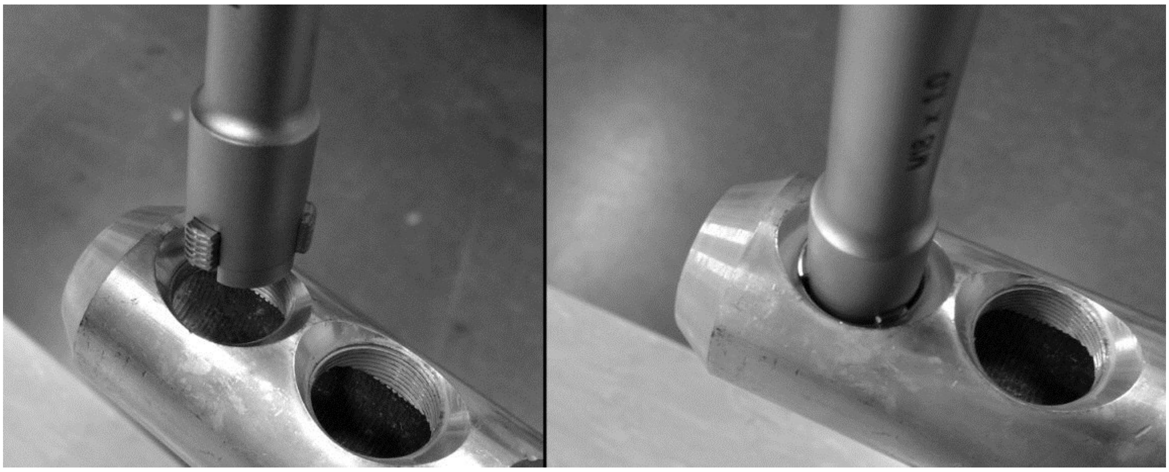

Figure 16 A micrometre for measuring the pitch diameter of internal threads. The micrometre is built for measuring only one specific thread diameter with a specific pitch.

The used thread gauges are precision instruments for measuring the tolerance of a thread. Each gauge can be used for identifying a specific thread having a certain nominal diameter and a specific pitch. Furthermore, each gauge is intended for identifying only a specific tolerance of the thread. That is to say that a thread gauge may identify for example only the thread M18x1 having the tolerance class 6g. The gauges for examining internal threads are staffs that have a precision fabricated thread in their end. The gauges for external threads have an internal thread to which external threads are compared by turning. The gauges have a thread that verifies the corresponding thread (a so-called Go feature) and a thread that rejects diverging threads (a No Go feature). For internal threads the gauge sticks usually have the verification thread in one end and the rejection thread in the other. The gauges for external threads usually consist of a separate component for verifying and for rejecting the thread under examination. Thread gauges for internal and external threads are displayed in figure 17 and 18.

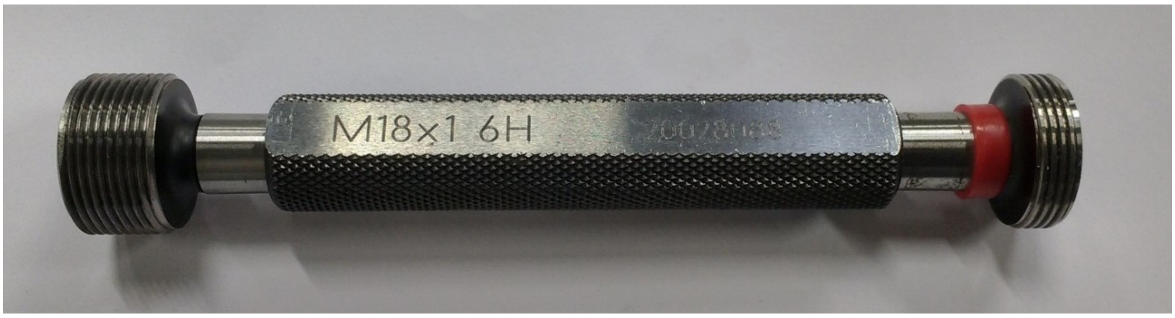

Figure 17 A thread gauge for internal M18 x 1 – 6H threads. The left end is used for verification and the right end marked with red is used for rejecting diverging threads.

Figure 18 Thread gauges for external M18 x 1 – 4h threads. The rejection gauge marked with a red dot can be seen on the right.

6.2.2 Evaluation of the Feel of Screw Couplings

The feel of the screw coupling can have a substantial effect on the purchaser's association concerning the quality of the connector. In a high-quality screw coupling the screw should turn at an even speed when it is turned at a constant torque. There should not be any irregularity in the feel when turning the screw. The screw should act smoothly and not tend to halt while rotating. The coupling should neither feel loose nor clank.

Manual testing was carried out in order to evaluate the feel of the screw coupling in the competing products. The screws were screwed by hand to their mating threads. There was no other resisting force than the friction of the thread. There was no cable inside the connectors. It was sensible to characterise the feel verbally and not use any descriptive figures. It was recorded whether the screw had some sort of grooves for shearing points. This was done because there was a presumption that the grooves may cause irregularity in the rotation of a screw.

6.2.3 Assessment of Thread Cross-sections

The operation and durability of the threads in different connectors is of interest in the scope of this thesis. To assess especially the durability of the threads the cross-sectional surfaces of the screw connections were examined visually. First, a length of cable was installed into the connectors under examination. After installation the connectors were sawed in half near the centreline of a screw. The formed cross-sectional surface was then fine ground using water sanding apparatuses to form a smooth surface for scrutiny. The grinding proceeded gradually from rough grinding paper to smoother and smoother.

Microscopic images of the cross-sectional surfaces were captured utilizing a microscope system that is controlled using a computer. The specimen was placed under the microscope and lit using a powerful adjustable spotlight. The instrumentation was controlled using the Infinity Capture software. The computer was connected to an Infinity Lite camera mounted to the microscope. The microscope utilises Optem magnifying optics.

The system was manually adjusted for each specimen. Once the lighting and optics were at a desired state the computer software was used for capturing and storing the microscopic images.

7 Results

Tests were carried out to identify factors affecting and ways to improve the quality of the screw coupling in an underground cable connector. The chapter presents the results of the torque-force tests starting from the pre-test that defined the sample size for the primary tests. In addition to the torque-force tests, the benchmarking findings are demonstrated. Tolerance examinations, thread feel surveys and visual observations on split threads were conducted to rival products.

7.1 Results of the Torque-Force Pre-Test

A pre-test was carried out on the torque-force measurement arrangement. The results defined the deviation of the used method. The sample size for the primary torque-force tests was determined based on this information.

7.1.1 Results Based on the Measurements

For defining the reference value for every run of the pre-test a trend curve was fitted for each graph of the results. 15 Nm was chosen to be the examination point for defining the ratio between torque and force. The trend curves expressed the dependency between torque and force. The force level at the chosen examination point of 15 Nm was defined based on the trend curve. The graphs were in this case analysed as if they were straight lines from the origin to the specified point. The angular coefficient of each run was used as the reference value of the run. The mean, variance and standard deviation of the pre-test runs are presented in table 8.

Table 8 Descriptive figures calculated for the torque-force pre-test series.

Descriptive figure	Symbol	Value
Mean	X	0.3497504 kN/Nm
Variance	σ^2	0.001544614 kN^2/Nm^2
Standard deviation	σ	0.039302 kN/Nm

The reference values of the runs of the pre-test clearly followed a normal distribution. The reference values were distributed into seven intervals having the same width. The histogram shown in figure 19 was formed based on the intervals and also it illustrates that the results are normally distributed. Formula 5 proposed dividing the results into five intervals but seven intervals illustrates the distribution more carefully.

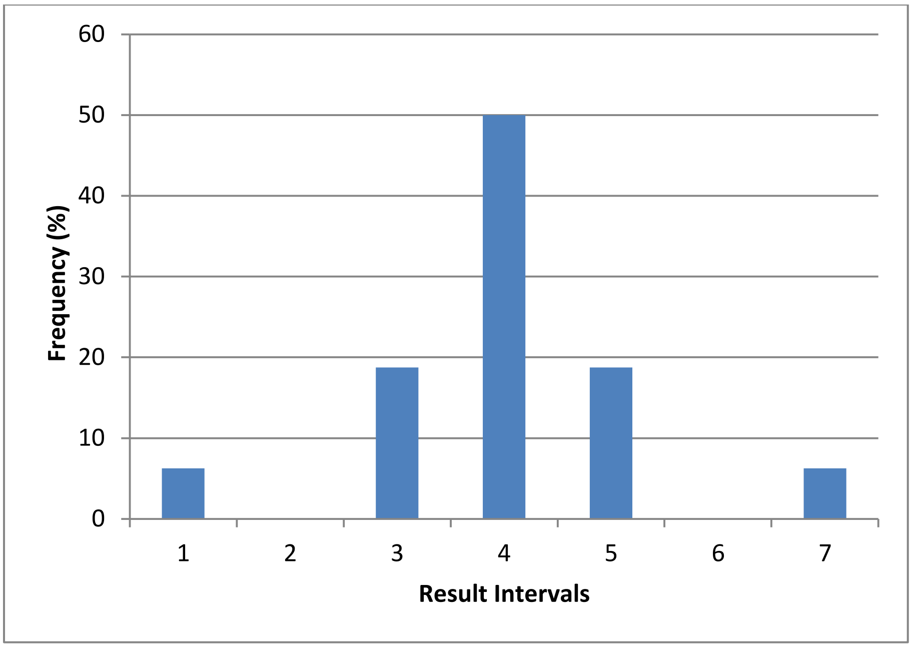

Figure 19 The histogram shows that the reference values of the pre-test results follow the normal distribution. The width of each interval is 0.027831429 kN/Nm.

7.1.2 Sample Size Determination Based on the Pre-test Results

After analysing the pre-test measurement results the relevant factors for calculating the sample size were resolved. A confidence level of 95 % and a β of 0.2 (power of 80 %) were chosen to be appropriate for this purpose. They are conventional and reasonable choices for engineering applications (Cohen 1969). A relatively small value was chosen for the minimum difference that is desired to be detected (u = 0.025 kN/Nm). It is practically 7 percent of the mean value of the results and more precise than the standard deviation of the results. As seen in table 9 the required sample size rounds off to 39.

Table 9 The determination of the required sample size. The number of test specimens (n) is determined based on the desired confidence and the deviation seen in the pre-test. Critical values of the Normal distribution are recorded according to Ayyub and McCuen (1997).

Figure	Symbol	Value
Confidence level		95 %
Significance level	α	0.05
	$\alpha/2$	0.025
Power		80 %
Beta	β	0.2
Critical Normal distribution value at $\alpha/2$	$Z_{\alpha/2}$	1.96
Critical Normal distribution value at β	Z_{β}	0.84
Difference to be detected	u	0.025 kN/Nm
Required number of test specimens	n	38.75262

7.1.3 Selection of the Thread Variations for the Tests

Three pairs consisting of internal and external threads were chosen for testing. The variations were M18 x 1 – 6H/4g, M18 x 1 – 6H/4h and M18 x 1 – 6H/6h. The thread variations were chosen above all based on the fit calculations described in chapter 5.4. It was desirable to test pairs that have a tighter fit, or less clearance, than the production versions of the components. The presumption was that a slightly tighter fit might produce a screw coupling that would feel like an even more high-quality thread connection than the present production version. In the best case a firmer fit might also further improve the mechanical function of the screw coupling.

The first pair (6H/4g) nearly matches the situation in a present underground cable connector. In the first two pairs the threaded block that has the internal thread is tin coated. The screws in every option are machined to the specified tolerance. They are not coated. This is what separates the 6H/4g pair from the actual product in which both the internal and external thread are tin coated. In the last option the threaded block is not coated either. The threaded blocks that are coated are first machined to a looser tolerance. After the tin coat they match the desired final tolerance. The three pairs are presented in tables 10, 11 and 12 along with the corresponding clearances. All of the calculations dealt with the threads according to the specific tolerance in which they were tested.

Table 10 The thread dimensions and clearances in a pair consisting of an M18x1 – 4g external thread and an M18x1– 6H internal thread (SFS 1990). The measurements are in millimetres.

External	Base Difference	Major Diameter d			Pitch Diameter d_2			Minor Diameter d_3		
Tolerance	A_O	max.	tol.	min.	max.	tol.	min.		max.	min.
4g	-0.026	17.974	0.112	17.862	17.324	0.075	17.249		16.747	16.600
	Difference 0.026	Min. clearance 0.026		Max. clear. 0.138	Min. clearance 0.026		Max. clear. 0.261		Min. clear. 0.170	Max. Clear. 0.553
6H	0.000	18.000			17.350	0.160	17.510	16.917	0.236	17.153
Internal	A_u	min.			min.	tol.	max.	min.	tol.	max.
Tolerance	Base Difference	Major Diameter D			Pitch Diameter D_2			Minor Diameter D_3		

Table 11 The thread dimensions and clearances in a pair consisting of an M18x1 – 4h external thread and an M18x1 – 6H internal thread (SFS 1990). The measurements are in millimetres.

External	Base Difference	Major Diameter d			Pitch Diameter d_2			Minor Diameter d_3		
Tolerance	A_O	max.	tol.	min.	max.	tol.	min.		max.	min.
4h	0.000	18.000	0.112	17.888	17.350	0.075	17.275		16.773	16.626
	Difference 0.000	Min. clearance 0.000		Max. clear. 0.112	Min. clearance 0.000		Max. clear. 0.235		Min. clear. 0.144	Max. Clear. 0.527
6H	0.000	18.000			17.350	0.160	17.510	16.917	0.236	17.153
Internal	A_u	min.			min.	tol.	max.	min.	tol.	max.
Tolerance	Base Difference	Major Diameter D			Pitch Diameter D_2			Minor Diameter D_3		

Table 12 The thread dimensions and clearances in a pair consisting of an M18x1 – 6h external thread and an M18x1 – 6H internal thread (SFS 1990). The measurements are in millimetres.

External	Base Difference	Major Diameter d			Pitch Diameter d_2			Minor Diameter d_3		
Tolerance	A_O	max.	tol.	min.	max.	tol.	min.		max.	min.
6h	0.000	18.000	0.180	17.820	17.350	0.118	17.232		16.773	16.583
	Difference 0.000	Min. clearance 0.000		Max. clear. 0.180	Min. clearance 0.000		Max. clear. 0.278		Min. clear. 0.144	Max. Clear. 0.570
6H	0.000	18.000			17.350	0.160	17.510	16.917	0.236	17.153
Internal	A_u	min.			min.	tol.	max.	min.	tol.	max.
Tolerance	Base Difference	Major Diameter D			Pitch Diameter D_2			Minor Diameter D_3		

The tin coating can have an essential influence on the operation of the threads. There was an explicit reason for not tin coating the screws. It was noticed that the tin coating process was hard to control for a small series of prototype screws. Verifying measurements were conducted using a Fischerscope coating thickness measuring instrument that utilizes x-rays for measuring. As achieving the desired coating thickness proved to be so troublesome the screws were simply machined to their final tolerance. The coating process worked better for the blocks having the internal threads and they received the desired tin coat. Of course, one series of the threaded blocks remained uncoated as already stated.

The selection of the three options was done based on the objective of the research and what was practical in terms of the resources available. 6H/4h and 6H/6h are chiefly slightly tighter than the first option that represents the production version. The calculated minimum clearances in options 6H/4h and 6H/6h are identical. The tolerances in the last allow slightly larger maximum clearances. Most of all the 6H/6h option was chosen to represent a situation in which there is no tin coating on the aluminium threads.

7.2 Results of the Torque-Force Test

As the purpose of the screw is to apply force to the conductor and hold it in place, the ratio between the force generated in the tip of the screw and the torque needed for tightening the screw was recorded as described in chapter 6.1. A basis of a good overall solution in the cable connector would be producing lots of force with little torque needed for turning the screw. The test results were processed as described in chapter 5.5.

Perhaps the most detectable result regarding the torque-force ratio is the distinction of the 6H/6h thread coupling compared to the two other options. The force in relation to the torque remains clearly lower than in the 6H/4g and the 6H/4h tests. This is no surprise as in that alternative both the screw and the threaded block were machined aluminium without any tin coating. Even though the threads were lubricated the lack of a tin surface dramatically increases the friction in the thread.

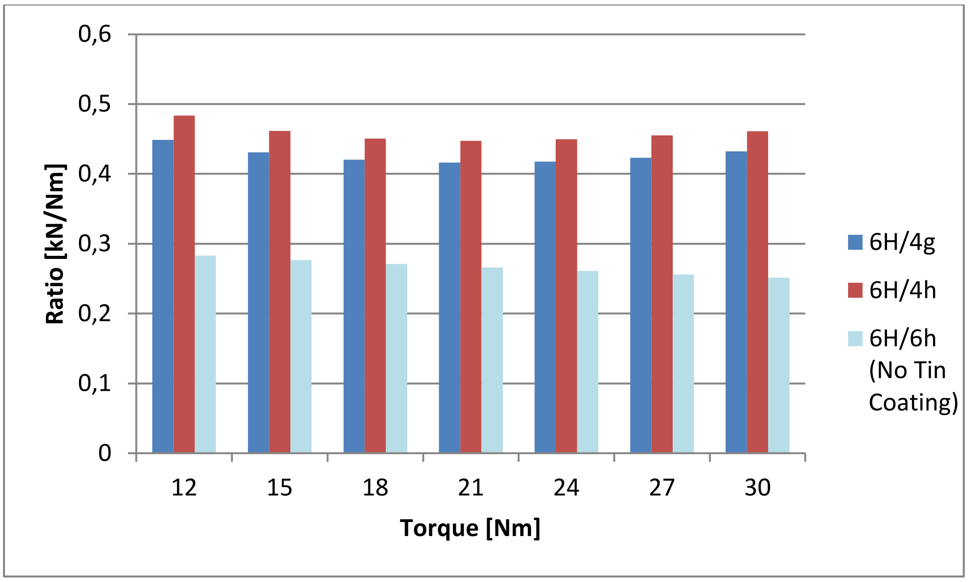

Figure 20 The ratio between the force and torque calculated at specific torque values.

Figure 20 demonstrates that the ratio clearly depends on the torque. That is to say that the ratio does not remain constant as more torque is applied. This phenomenon can be seen also when fitting the trend curves to the results. The curves are polynomial and by no means straight lines. The principal rule for all of the thread options was that the ratio decreased as the torque was increased. Yet, the ratio did somewhat fluctuate during tightening especially in the cases of 6H/4g and 6H/4h. Again, this is entirely in line with the polynomial trend curves.

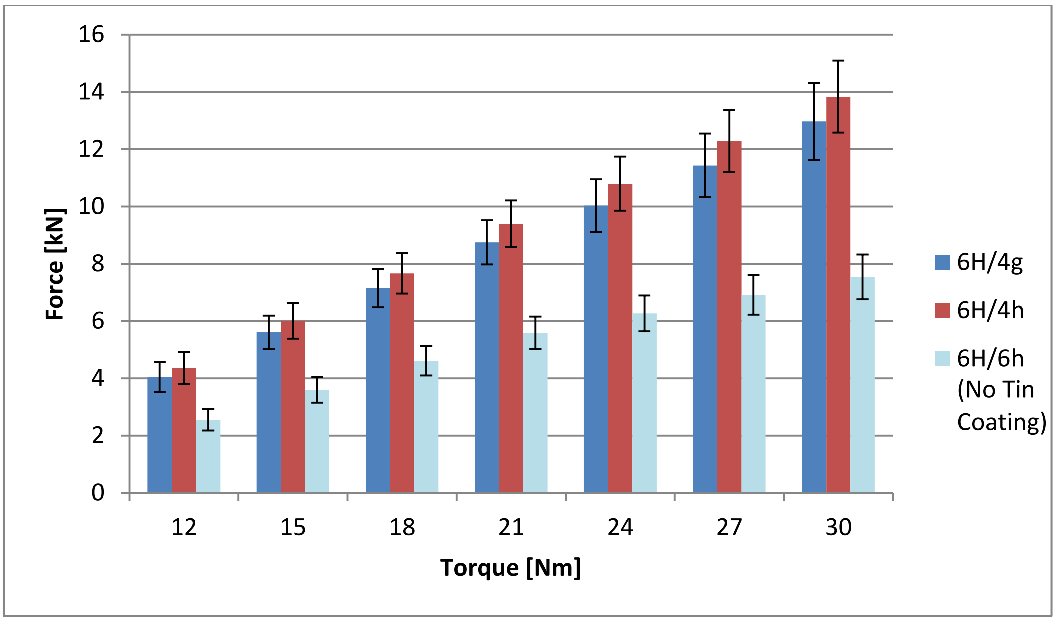

Figure 21 The force generated at specific tightening torques. The black error bars relate the standard deviation of the results is that specific position.

The comparison between 6H/4g and 6H/4h shows that 6H/4h produces more force down the line. This can be seen in figure 20 and figure 21 alike. In both cases the ratio and the force evolve in a relatively similar manner as the torque is increased. The error bars in accordance with the standard deviation of the results in figure 21 indicate that margins of error for 6H/4g and 6H/4h partly overlap each other. Due to the sufficient sample sizes 4h-6h can be decidedly found to produce slightly more force. The standard deviation is handled further based on figure 22.

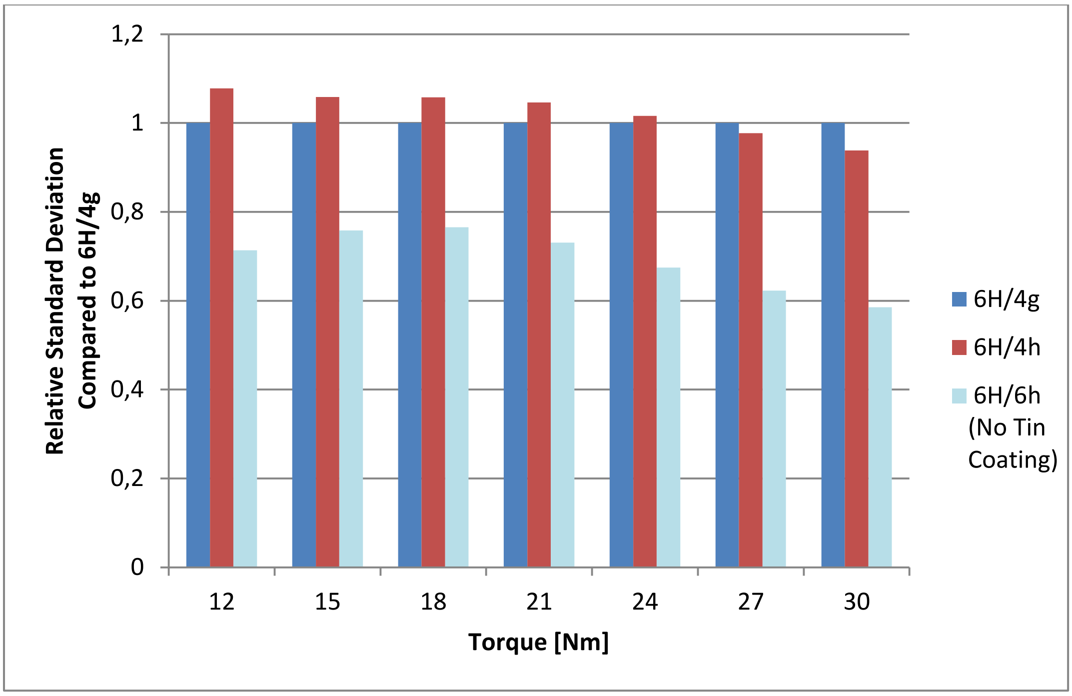

Figure 22 The standard deviation in relation to the deviation of the 6H/4g results. The standard deviation of 6H/4g equals 1 as all of the options are compared to it. The standard deviations are determined at the specific tightening torques.

The standard deviation of each of the tested options fluctuates as the torque changes. It is notable that the standard deviation of the 6H/6h option is evidently lower than of the other options. The deviations of 6H/4g and 6H/4h are comparatively alike. Figure 22 indicates that the deviation of 6H/4h is first higher compared to 6H/4g but the order is reversed as the torque increases. Though the friction is higher, it likely varies less in the 6H/6h option where both threads are machined surfaces. While the tin coating reduces friction, it adds some sort of fluctuation to the surface of the thread.

The results of the torque-force tests cannot be directly extrapolated to actual connectors. The ratio of torque and force is most likely different in the true application. Nevertheless, there is no crucial reason to question that the slight superiority of the 6H/4h pair over the 6H/4g option would not be valid in the actual product also. If the tolerance is changed in an actual product the standardized tests must, of course, first be performed.

7.3 Benchmarking Findings

Underground cable connectors from multiple manufacturers were tested for benchmarking purposes. Tolerance examinations, thread feel assessment and visual observations on split threads under a microscope were conducted. First, the following pictures present some of solutions offered by various manufacturers for connecting underground cables.

Figure 23 A connector utilizing shear-head screws which are placed in an angle.

Figure 24 Shear-head screws placed in a straight line on one side of the connector.

Figure 25 Screws which have multiple grooves in the thread for shear points.

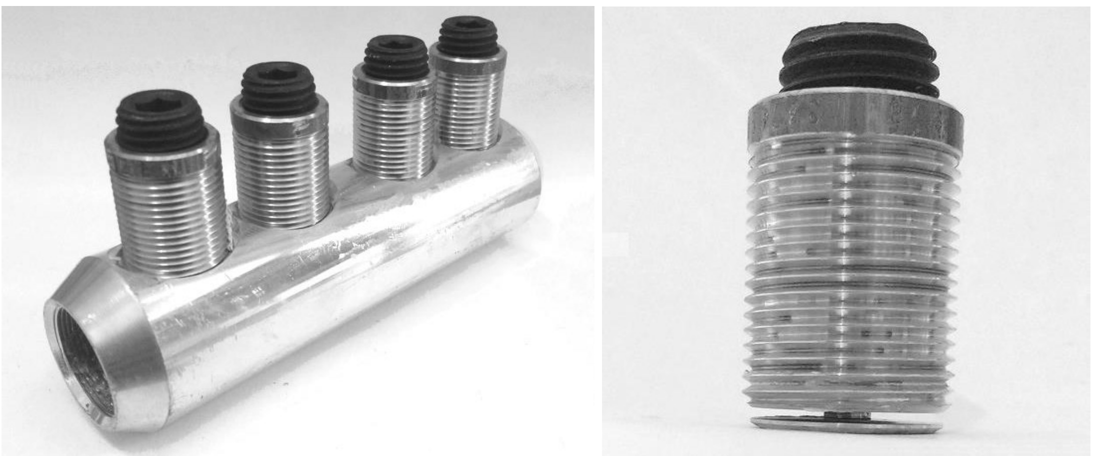

Figure 26 A connector using special two-part screws placed in a straight line.

Commonly at least the head of the screws is designed to shear of as the screw is tightened to a specific torque. The screws in figures 23 to 25 represent this type. The connector in figure 25 also has grooves in the threads for specific shear points. As the figures 23 to 26 show, the screws may be placed either along a straight line or in different angles. The screws in figure 26 have a rather special design. The screw tip has a plate that breaks loose under loading. The plate then remains stationary and the rest of the screw rotates pressing against it. The same two-part screw has a threaded pin inside the outer sleeve. As the defined tightening torque is achieved the sleeve of the screw shears off near the surface of the connector body taking the pin with it. The two-part screw after installation is seen later on the right half of figure 27.

Commonly the screws are made out of some type of aluminium or brass alloys. The connector bodies are machined out of aluminium alloy. Tin coating is usually used both on the screws and on the connector bodies. In the connector in figure 26 only the connector body is tin coated and the screws remain uncoated.

7.3.1 Tolerance Examination

Tolerances of both the internal and external threads were examined using thread gauges. Measurements were also performed using micrometres.

The selection of thread gauges available restricted the possibilities of completely figuring out all of the used tolerances in the product assortment under examination. The thread size of the screw connection lies roughly in the same neighbourhood in all of the examined connectors. Some variation exists in the pitch and also in the nominal diameter of the threads. The minimum and maximum nominal cable diameters are not equal in the connectors which may partly explain the light differences in the threads. The thread tolerances of the examined connectors are compiled in table 13. In addition to using thread gauges the external tolerances were estimated based on micrometre measurements regarding the major and pitch diameter of the screws. The minor diameter of the internal thread was also measured using a suitable micrometre.

Table 13 The thread sizes and the thread tolerances of the examined underground cable connectors. The examination was done using thread gauges. A thread gauge for identifying each of the internal threads was not available. The measured external tolerances are based on the micrometre measurements regarding the major and pitch diameter of the screws. The external tolerances based on the measurements are to be considered approximate.

Connector	Thread	External (Gauge)	External (Measured)	Internal (Gauge)
Connector 1	M18x1.5	6h too tight	4h,4g,4e, 6h,6g	6G
Connector 2	M20x1.5	6g or 6h	6g	6G
Connector 3	M18x1.5	6e	6e, 6g	6G
Connector 4	M18x1	6h	4e	-
Connector 5	M18x1.5	6h	8g, 8e	-
Connector 6	M18x1	4h	6h	6H
Connector 7	M18x1.5	6h	6e, 6g	6G

The evaluations using thread gauges should be reasonably dependable. Yet, it must me acknowledged that the variety of thread gauges available did not cover all of the tolerances that may be at stake. There was not a rejection gauge for all of the tolerances either. The measurements using micrometres should be considered approximate. This is due to the fact that the chance of human errors is evident when using a micrometre even if several measurements are made to check the result. There was not an instrument available for measuring the minor diameter of the external threads, the pitch diameter or major diameter of the internal threads. Also for example the coating of the screws may have a substantial effect on the micrometre measurements: the coating thickness may vary and the micrometre may or may not deform the coating. The measurements performed using micrometres are gathered below in table 14.

Table 14 The dimensions of the internal and external threads of the examined underground cable connectors were measured using suitable micrometres. Several measurements were performed but the measurements should still be seen approximate. The measurements are in millimetres.

Connector	Thread Size and Pitch	External Pitch Diameter	External Major Diameter	Internal Minor Diameter
Connector 1	M18x1.5	16.94	17.95	16.54
Connector 2	M20x1.5	18.85	19.82	18.61
Connector 3	M18x1.5	16.87	17.87	16.42
Connector 4	M18x1	17.20	17.92	17.10
Connector 5	M18x1.5	16.77	17.70	16.70
Connector 6	M18x1	17.25	17.84	16.93
Connector 7	M18x1.5	16.85	17.79	16.47

The recommended tolerance classes according to the ISO 965-1 standard for internal and external threads were presented in tables 4 and 5 in chapter 4.2.3. It appears that most commonly manufacturers have chosen to use either the first (6H) or second (6G) option recommended in the ISO 965-1 standard for the tolerance of internal threads. Based on the examination there is slightly more variation in the tolerance chosen for the screw thread. The chosen solutions revolve around the best solutions. The least favourable options mentioned in the standard are not used.

Examination was also conducted concerning uncoated components. As machined screws were examined using thread gauges, it was discovered that the thread itself is in accordance with the desired tolerance but the grooves machined to the thread may cause irregularity. The grooves in question can be either the grooves for the shearing points or the grooves for the tightening tool on some screws. The thread gauge often stops as it meets the first groove in the thread. Apparently minuscule deformations or chips may sometimes be formed in the edges of the grooves during machining. These deformations stop the thread gauge.

Occasionally tinned screws would not start to rotate into the thread gauge. The pitch diameter and major diameter were correct nevertheless. Upon further investigation it was discovered that especially the edge of the first thread can suffer light damage likely in the following stages after machining. The possible origin of dents might relate to a cleaning process, the coating process itself or drying of the screws. Also the way the components are handled between the phases can be to blame. Even though the screws would not go into the thread gauge the screws perform faultlessly in conjunction with the connector body. A thread gauge for external threads is in practice a particularly tight internal thread that very precisely matches the corresponding external thread. If there are even light dents in the external thread this may cause the gauge to reject the thread. It is also worth acknowledging in this connection that the tin surface itself might also cause problems if it is not evenly settled in the thread.

The internal threads inside connector bodies work flawlessly and match the appropriate thread gauge. Throughout the manufacturing process the internal threads are safe from possible knocks that could cause dents.

As stated also earlier in chapter 4.2.3, according to the ISO 965-1 standard the most favourable option for an internal thread tolerance is 6H and for an external threads 6g if medium tolerance quality is chosen. If the threads are coated the basic rule is that these tolerances apply before coating. After coating the threads should not transgress the maximum material limits for tolerance positions H or h. Second best tolerance options in the normal length of thread engagement include 6e, 6f and 4h for external threads and 6G for internal threads. 4h is the recommended tolerance position for the external thread if fine tolerance quality is desirable. (ISO 1998b) Quite commonly the screws and internal threads in the examined connectors utilise some of the above-mentioned tolerances.

7.3.2 The Feel of Screw Couplings

As explained in chapter 6.2.2 connectors were evaluated also based on the feel of their screw coupling. The screws were manually screwed into the connectors without a cable inside the connectors. The evaluation results are compiled in table 15.

Based on the evaluations, it is rather common that there is some sort of a free play in the feel of the screw couplings. The screws were so loose in some of the tested specimen that the connectors even rattled if they were swung back and forth. A clear minority of manufacturers use grooves in the screw thread area for specified shearing points. As it was noticed when examining the screws with thread gauges, there may be imperfections in the thread on the edges of the machined grooves. These imperfections are a plausible cause of irregularity in the feel of the screw. The light dents that may result from the coating process are another issue involving coated screw threads.

The slight differences in the tolerances and also in the pitch of the thread are possible factors affecting the feel. Still, in the conducted evaluations, a dependency between the pitch and the feel could not be detected. Likely other factors are more dominant. Also actual differences in the manufacturing quality can naturally influence the affair. It is worth highlighting that all of the tested screw couplings undoubtedly perform their intended task even if the feel of the coupling was not ideal in this test.

Table 15 Evaluation of the feel of the screw couplings. Free play means that the screw rocks inside the internal thread of the connector body. That is to say that the coupling does not feel firm.

Connector	Grooves in the Thread for Shearing Points	Thread Feel
Connector 1	-	Turns smoothly, clear free play
Connector 2	-	Turns smoothly, clear free play
Connector 3	-	Turns smoothly, clear free play
Connector 4	Yes	Tends to seize while turning, quite firm
Connector 5	-	Turns smoothly, clear free play
Connector 6	-	Turns smoothly, very firm
Connector 7	-	Occasionally tends to seize while turning, clear free play
6H/4g test piece	-	Turns smoothly, slight free play
6H/4h test piece	-	Turns smoothly, very firm
6H/6h test piece	-	Turns smoothly, clear free play

The test screws and the threaded blocks that were manufactured for the torque-force tests were evaluated also from the perspective of the screw coupling feel. All of the options turn very smoothly but there are observable differences in the free play. The 6H/4g matches the actual product rather well in terms of the free play that can be easily noticed. The 6H/4h feels firm and does not rock. The 6H/6h clearly rocks. The tighter fit of 6H/4h compared to 6H/4g most apparently explains the firmer feel. The minimum clearances in 6H/4h and 6H/6h are the same but 6H/4h has smaller maximum clearances. This added to the absence of tin in 6H/6h account for the clearly firmer feel of 6H/4h.

7.3.3 Thread Cross-section Images

The connectors under assessment were sawn in half and fine ground as described earlier in chapter 6.2.3. A length of cable was installed in the connectors and the screws were tightened before sawing the connectors in half. Three microscope images were taken of every connector: a general view illustrating the whole thread and a close-up from the left and right side of the thread. Selected microscope images of the connectors cut in half are presented in this chapter for demonstrating the made observations.

It seems to be almost a rule that the screws in connectors drift towards some side of the internal thread. This can be seen in figure 27. A possible reason for the screws to drift to one side could be the fact that the screws are placed in an angle on the connectors and not directly in the centreline of the connector body. On the other hand, this cannot be the only explanation since the drifting of the screw was observed also on connectors on which the screws are straight in the centreline of the connector.

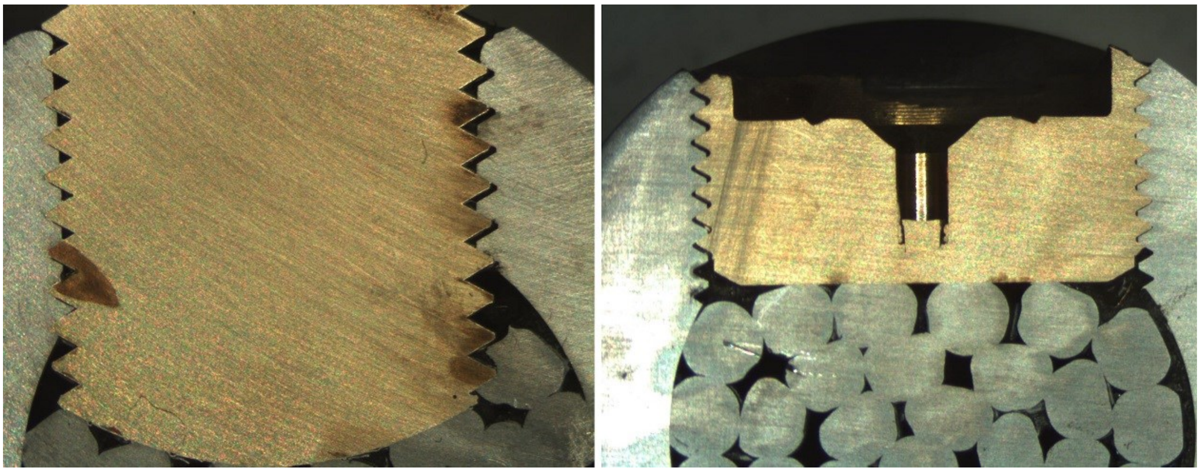

Figure 27 It was observed to be common that the screws drift to either side of the internal thread. On the left side the screw has drifted to the left and on the right the screw has drifted to the right. Conductor strands can be seen beneath the screws.

Another remark that can be made based on the connector on the left side in figure 27 concerns the shape and size of the bore of the internal thread. The hole appears to be conical in the way that it tapers downwards. In addition to tapering the bore appears to be oversized throughout. These factors do not seem to make the connector inoperable, even though the contact area of the thread is clearly reduced.

On some connectors the reduction of contact area due to another reason likely had some consequences. It was detected that on part of the connectors the internal thread was deformed by the screw. The deformation took place on some of the connectors on which the screw drifted to one side during tightening. The deformation occurred on the side of the internal thread from which the screw diverged. The deformation is likely a result of the decreased contact area of the thread on the side that is in question. The material properties naturally play an essential role in the affair. An example of the foregoing is shown in figure 28.

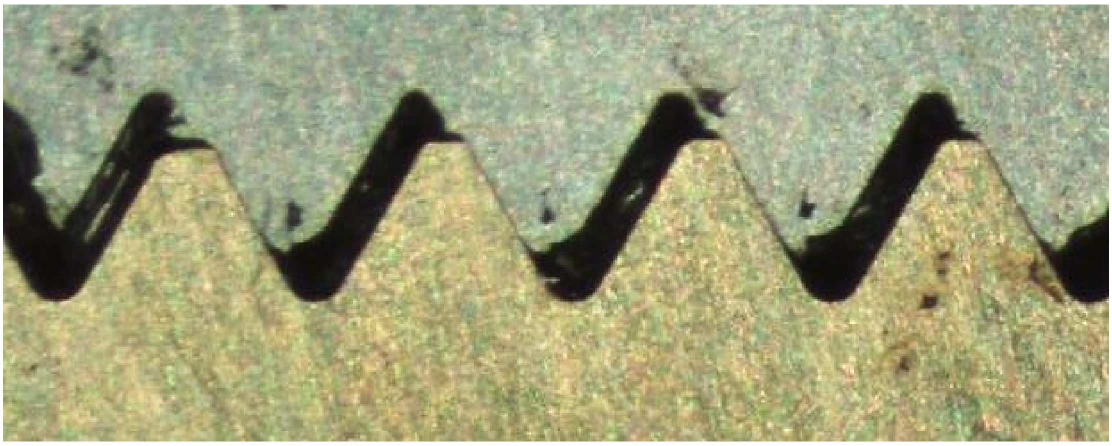

Figure 28. On some connectors the internal thread was deformed by the screw during tightening. The deformed internal thread of the connector is seen on the top of the picture and the screw thread on the bottom. The screw diverged from the side on which the deformation took place.

The thread shape of one of the connector body distinguishes from the rest. The crest of the thread is neither sharp nor blunt. As it can be seen in figure 29, there is a groove that travels along the crest of the thread. It looks as if the same bore has another thread that has the same pitch but different depth. A possible reason for this shape might have something to do with trying to introduce elasticity to the coupling. Other reasons could relate to lubrication, coating or reducing the influence of possible chips. It is difficult to detect any deformation in the thread with certainty. The same thread form can be observed also in the connector bodies of a couple of other manufacturers. As seen in figure 28 the crest of the thread deforms in the connector in question. The corresponding phenomenon can be seen also in another connector. The yielding under tightening is most likely deliberate. The goal could be trying to prevent deformations in some unwanted sections of the thread.

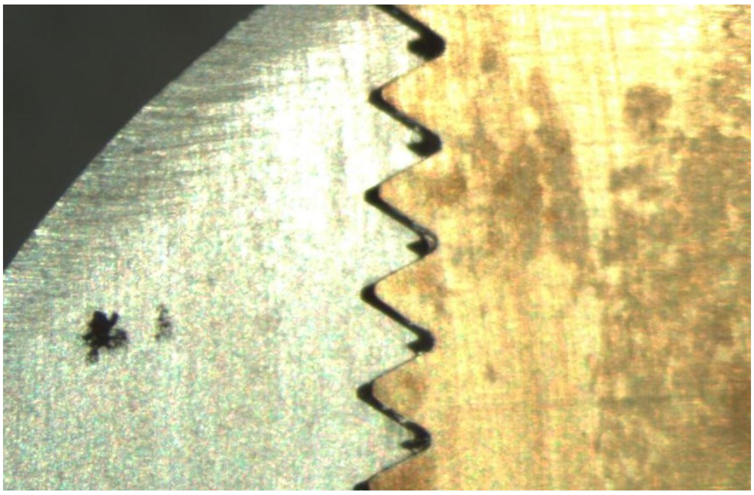

Figure 29 There is a groove that travels along the crest of the internal thread in the connector body.

Also a different type of an observation concerning the crest shape in the internal thread was made. As it can be seen in figure 30, the crest of the internal thread appears to be sharper on the left side compared to the right. The look of the thread suggests that the thread bore and tapping are not entirely concentric.

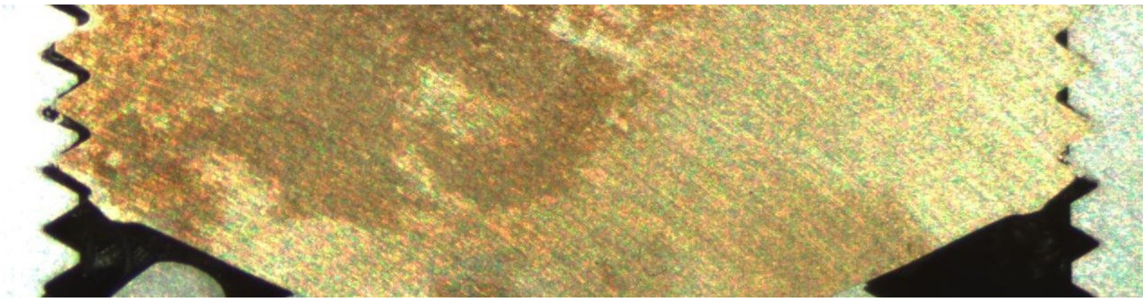

Figure 30 A difference in the shape of the crest is observable when comparing the sides of the internal thread. The crest on the left is sharper. It seems the thread bore and tapping are not entirely concentric.

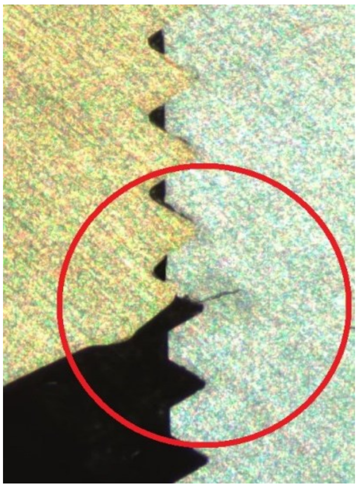

Figure 31 A crack was discovered in the thread of one of the examined connectors.

A small crack was discovered in the thread of one of the examined connectors. The crack is highlighted in figure 31. The crack is located in the root of the first thread closest to the conductor. As a result of the crack the stress is doubtlessly now carried by the rest of the thread. And as it was earlier noted, primarily most of the stress is carried by the first engaging thread. Deformation was commonly observed in many of the tested connectors. Therefore it is interesting that a crack was discovered rather than a deformation of the thread profile.

8 Conclusions

The right techniques and good quality products ensure the reliability of the electricity transmission network. Underground cabling is conquering market shares from overhead lines even though the construction of underground cabling costs more. Not least due to the high costs, attaining a long useful life for the underground cable network is important. The possibly corrosive conditions underground and the fluctuating electrical loads set quality requirements in terms of the performance, reliability and durability of the used components. Underground cable connectors undergo comprehensive standardized testing before they reach the markets. This ensures the components perform faultlessly in the demanding conditions.

Quality consists also of other aspects than simply the operation of the product. The appearance of a product may not affect its performance. Nevertheless, factors such as shapes, colour and surface finishing affect the way a customer perceives the overall quality of a product. Often the customer is forced to make decisions based on subjective experiences and mental images over the products. The mental picture of a product is formed based on the elements which are easily distinguished. The expected quality can be based on advertising, the company image, earlier experiences and competing products.

Producing high quality products can considerably promote the success of a company. Quality related problems induce financial losses following from rework, scrap and returns. Productivity can be enhanced by investing in quality improvement. Also profits can be increased through satisfying customers with better quality. Satisfied customers will gladly do business again. Better quality over competitors helps in raising market share. Quality improvement efforts may first even increase costs but, as above stated, the investment is worth it. There are several methods and frameworks for improving quality. It can be collectively noted that tracking the operations of the organisation plays a key role in the efforts. Quality improvement is a persevering undertaking that concerns every branch of an organisation.

Standardization aims to ensure the safety and compatibility of devices and activities. Standards are uniform solutions prepared and approved in a specific way. Standardization simplifies legislation, design, communication and international trade. Also costs are decreased. Standards often include quality requirements and they are used in certifications. Standards define notations, ways for expressing matters, variables and units. Standardization is managed in international or continental parent organizations. National standardization organizations implement standards locally. Standardization of threads and fasteners most of all assures conformity of components.

Research was carried out to identify the factors affecting the perceived quality and the overall operation of the screw coupling in an underground cable connector. An important objective was determining the significance of the thread tolerance of the connector screw. The ratio between the torque needed for turning the screw and the force generated at the tip of the screw was studied using the testing arrangement developed as a part of the research. Benchmarking of rival products was conducted using thread gauges and by assessing the feel of the screw couplings by hand. Additionally connectors were cut in half along the longitudinal axis of the screw. The formed cross-sections were examined under a microscope.

The results of the torque-force tests suggest it is worth looking into the option of shifting to utilise 4h screws in conjunction with a 6H thread instead of 4g screws. In the tests 4h screws produced slightly more force at any given tightening torque. As the torque increased to a certain level, the deviation of the torque-force ratio also reduced to lower than of the 4g screw. The differences were observable, though not very notable. The examinations concerning the feel of the screw coupling indicated also that a coupling having a 4h screw feels firmer than a 4g screw. This is a corollary of the smaller clearance. Clearly, it is highly recommended to use tin coating on the threads instead of utilizing machined aluminium surfaces against each other. The lower friction offered by the tin coating substantially increases the attained force at any given tightening torque.

The benchmarking of thread tolerances showed that there is some variation among the manufacturers in the used thread tolerances. The majority of the used tolerances belong to the most or second most recommended options in the ISO 965-1 standard. Options belonging to the medium tolerance quality were prevailing.

In accordance with the ISO 965-1 standard the preferable option would be using a 6H thread in the connector body and a 4h thread in the screw. This applies if it is desirable to use a thread having a medium tolerance quality on the connector body and a thread with a fine tolerance quality in the screw. In practice the 4h screw would be machined according to looser dimensions and it should meet the dimensions of the tolerance position h after coating. Proceeding in this matter calls for testing with an actual connector body that utilises screws manufactured to meet the 4h tolerance.

The evaluations concerning the feel of the screw couplings show it is rather common that there is some sort of a free play in the feel of the screw couplings. The screws mainly revolve smoothly when rotated by hand. A clear minority of manufacturers use grooves in the screw thread area for specified shearing points. The slight differences in the tolerances and also in the pitch of the thread are possible factors affecting the feel. Also actual differences in the manufacturing quality can naturally influence the affair. The machined grooves on screws can clearly cause irregularity in the screw coupling feel. If there are small deformations or chips in the edges of the grooves, they clearly affect the feel when turning the screws by hand. Though there are no problems in the operation of the connectors, disposing of the imperfections in the edges of the grooves would most definitely enhance the mental image on the quality of the connector. The edges of the grooves could possibly have chamfering or alternatively something else has to be developed in the manufacturing process.

The scrutiny of the split connectors under a microscope revealed many elements that would be otherwise difficult to discover. The screws tend drift to either side of the internal thread rather commonly basically in all of the connectors. Most apparently this has no effect on the operation of the connectors. The threads in the connector body deform on many connectors under tightening of the screws. Some manufacturers have introduced an internal thread crest shape that yields under loading.

It was also evidently detected that the tin coating process may cause imperfections to the finished screw threads. The principal problem is not necessarily the coating process itself. The working phases related to coating, such as washing and drying at different phases, may be the source of the issues. The whole work process needs to be analysed to figure out and eliminate the exact cause or causes of the damages in the thread.

Attention should be paid also to the machining process of the internal thread in the connector bodies. The microscope pictures showed an internal thread on which the crest is not equally sharp around the thread. The look of the thread suggests that the thread bore and tapping may not be entirely concentric. Another peculiar observation concerning the internal threads was the crack noticed under the microscope on one of the connector bodies. Resolving this could be done by enhancing the mechanical structure or possibly by altering the materials used. The significance of the yielding crest shape observed on some benchmarked connectors could still be further looked into.

Testing could be conducted regarding the thread pitch in the connector. Testing can be done to resolve how the pitch affects the torque-force relation, the perceived quality and the mechanical durability of the screw coupling. The utilization of lubricants and different types of coating materials are subjects that can be studied as they undeniably affect the function and possibly the feel of the screw coupling. Tests with brass screws could also be carried out with the above-mentioned interests.

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