Curtin University of Technology

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Cost study for power system utilities

Final Year Engineering Thesis, 2009

By

Sebastian Broecker

A thesis submitted to the Department of Electrical and Computer Engineering in partial fulfillment of the requirements as an exchange student.

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AUTHOR: Sebastian Broecker FAMILY NAME: Broecker GIVEN NAME: Sebastian				
DATE: 12th June 2009	SUPERVISOR: Dr. Ahmed Abu-Siada			
DEGREE: Exchange with FH-Aachen Germany and HSZuyd, Netherland	OPTION:			
ABSTRACT: This thesis presents the investigation of the costs of investing in a new transformer compared to the maintenance of an existing one. A detailed research on the different technical possibilities to maintain transformers has been conducted. Apart from that, the transformer failures and the following cost issues are shown in this paper. Further the Superconducting Magnetic Energy Storage (SMES) technology has been compared with other technologies taking cost and technical aspects in consideration. The paper includes description of SMES units and other available technologies.				
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SYNOPSIS

This thesis presents the investigation of the costs of investing in a new transformer compared to the maintenance of an existing one. A detailed research on the different technical possibilities to maintain transformers has been conducted. Apart from that, the transformer failures and the following cost issues are shown in this paper. Further the Superconducting Magnetic Energy Storage (SMES) technology has been compared with other technologies taking cost and technical aspects in consideration. The paper includes description of SMES units and other available technologies.

Sebastian Broecker
Student No: 14257285

Flat 46 Room 8, Don Watts House
Kurrajong Village
Kyle Avenue, Bentley 6102
Western Australia

June 12th, 2009

Professor Syed Islam
Department of Electrical and Computer Engineering
Curtin University
Bentley
Western Australia WA 6102

SUBMISSION OF THESIS

Dear Sir,

I hereby submit the report "Cost Study for power system utilities" as my thesis to meet the requirements of the Department of Electrical and Computer Engineering in completion of Engineering Project 402. This course was taken as part of an exchange program to complete my degrees: "Dipl.-Ing. (FH) Betriebswirtschaftliche Technik, Studienrichtung Elektrotechnik" and "Elektrotechniek, afstudeerrichting Commerciële Techniek".

This report is entirely my own work except for the assistance received from my supervisor and those mentioned in acknowledgements.

Yours Sincerely,

Sebastian Broecker

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ACRONYMS

A/D converter	analog-to-digital converter
ASTM	American Society for Testing and Materials
CAES	Compressed air energy storage
CES	cryogenic energy storage
CS	cryogenic system
CTC	continuously transposed cable
CU	control unit
DBPC	Di Butyl Para Cresol
DGA	dissolved gas analyses
DP	degree of polymerization
DSP	digital signal processor
EES	Electrical Energy Storage
FRA	frequency response analyse
FRA	frequency response analyse
HTS	high-temperature conducting coils
IEC	International Electrotechnical Commission
LA	Lead acid batteries
LTS	low-temperature conducting coils
PCS	power conditioning system
PHS	pumped Hydroelectric Storage
SCM	superconducting coil with the magnet
SMES	superconducting magnetic energy storage unit
TDCG	total dissolved combustible gas
TES	Thermal energy Storage
UPS	uninterruptible power supply

1. INTRODUCTION

Every year millions of dollars are lost through failures in power transformers. Apart from that, the liberalisation of the energy market in the last years (especially in Europe) puts high pressure on the different operators to review their maintenance programs and to work more efficiently. Therefore the desire to save costs in maintenance and operation of power system utilities is very high.

Further the need for storage applications and high quality energy rises to gain a higher efficiency or to work with nowadays applications. This is obvious if the growth of the market of alternative energies is considered. Energy produced through wind or sun power is only available during specific times and has to be saved if it should be provided all day long.

1.1 Objectives

Therefore the objectives of the thesis are:

- To study the costs of power transformer regular maintenance and comparing it with the current price of a new power transformer
- To investigate the economic use of superconducting magnetic energy storage (SMES) units in Power System application and to compare its costs with other available technologies.

1.2 Thesis Structure

This thesis is divided into two different and very distinct parts: chapter 2 and 3. These chapters have then been broken down into detail.

Chapter 2 starts with the cost research of the transformers. It gives a technical overview of a transformer, the different maintenance difficulties and monitoring possibilities that could solve these. A research on the costs is then made.

Chapter 3 is about the SMES unit and other available technologies. The techniques of SMES units and descriptions of alternative technologies are also given.

The paper ends with a final summary of what has been found and provides recommendations for possible future research.

2. TRANSFORMER

A transformer is a device that is part of an energy converting system. In this conjunction, a transformer can be found in low power but as well in the high power areas. It is an elementary element in the transfer of energy from the power plants to the customers. Through a transformer, it is possible to work on an economic generator voltage but as well as on the power utilisation needed by a specific device.

Depending on the application the transformers are of different sizes, ranging from fingernail size units to multi-ton giants for power stations[2]. In this paper the main focus is to look at power transformers for power factories.

2.1 Technical Theories of Transformers

A transformer has two or more coils. These coils are called primary winding and secondary winding. If a power source is connected to one of these coils, a flux links them. This flux depends on the voltage of the power source, its frequency and the number of turns (N) of the windings. Through the flux, a voltage is induced in the secondary winding, which depends on the turns in the latter, ‘the magnitude of the mutual flux and the frequency’[3]. Generally, the windings could be connected through the air but because of efficiency reasons this is mostly done with ferromagnetic materials such as iron. Such transformers are called iron-core transformers.

The winding (normally the primary one) that is connected to a power source has fewer amounts of turns than the secondary one, the voltage on the secondary winding is stepped down. If on the other hand, it has more turns than the secondary one, the voltage goes up. This is shown in the following equation:

$$\frac{v_1}{v_2} = \frac{N_1}{N_2}$$

As already mentioned the voltage on the second winding depends on the amount of windings and is based on electromagnetic induction. The physical law behind this process is Faraday's law[4]:

$$v_1 = e_1 = \frac{d\lambda_1}{dt} = N_1 \frac{d\varphi}{dt}$$

With:

λ_1 = flux linkage of the primary windings

φ = flux in the core linking both windings

N_1 = number of turns in the primary winding

Because both windings are connected through the flux the electromagnetic field in the second winding is:

$$v_2 = e_2 = N_2 \frac{d\varphi}{dt}$$

This is only valid if it is assumed that the transformer is an ideal one where losses and leakages are negligibly small. Then the voltage is transformed in direct ratio to the turns in the windings. This ratio is often called transformer ratio.

$$\frac{N_1}{N_2} = a$$

For the fact that the regarded transformer is an idealised one, it is already mentioned, that $v_1 = e_1$. If a load is connected to the secondary winding a current i_2 will flow through it. Consequently the flux in the core is equal to a non load situation and therefore there must be a current i_1 forced by v_1. It is already said, that the magnetic field of the primary current $N_1 i_1$ must be opposite and equal to $N_2 i_2$

$$N_1 i_1 = N_2 i_2$$

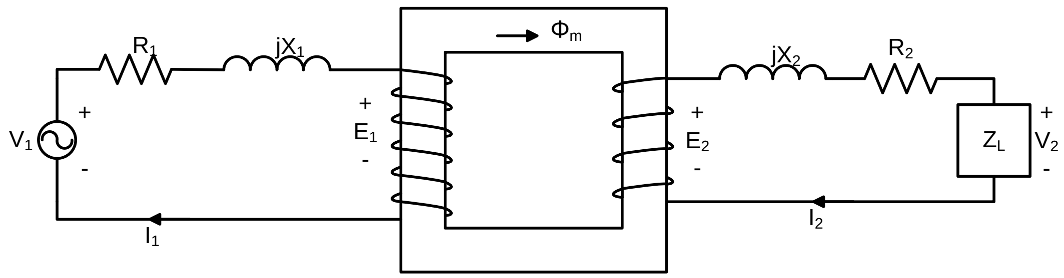
$$\frac{i_2}{i_1} = \frac{N_1}{N_2} = a$$

Accordingly the primary the secondary currents of the transformer are transformed in the inverse ratio of turns[5].

In contrast to that, a non-ideal transformer is not lossless. It starts with a resistance in the winding which results in the input not being equal to the output voltage. It is important to remember this during the dimensioning progress of a transformer[3]. Consequently the voltage in the winding is not exactly equal to the magnetic field which results in efficiency less than 100%.

A second difference to an ideal transformer is leakage. The flux created by the winding flows not only through the iron core. A part of it - the leakage flux – goes through the air. Figure 2-1 describes a non ideal transformer including the leakage and resistances in it.

Figure 2-1: schematic view of a non ideal transformer



Apart from that there are different types of transformers. One example is a multiwinding transformer. This transformer has three or more windings to connect different circuits with different voltages to one transformer. This can also be done by using more than one transformer. However, it is not efficient and of course not economic.

Another transformer type is an autotransformer.[6] This is similar to a normal two-winding transformer with the exception that the two windings are connected electrically or in another case only one winding with common turns is used. Because of that, the high and the low voltage sides are not isolated from each other. The autotransformer can be used in almost all areas where a two-winding transformer is used with the advantage that it is cheaper, has more power and is more efficient in similar power ratings. Nevertheless there is no isolation between the two voltages sides.

The third type of transformer is the three-phase transformer. In this application area, a bank of three single-phase transformers can be connected to get a three-phase circuit (Δ or Y connection) or there is the possibility to use a three-phase transformer. In the case where three different single phase transformers are used, there are several ways to connect these to build a three-phase circuit.

The following summary gives a small overview[6] of possible connections to build a three-phase transformer bank:

Y–Δ: This connection type is often used for step down applications, like high voltage to low voltage. The characteristic of this connection is that the neutral point of the high voltage side can be grounded.

Δ –Y: This configuration is used for step up voltage.

Δ–Δ: In this configuration, one transformer can be removed for maintenance or repair while the other two will still operate as a three-phase bank but with a rating reduced by 32%. Another name for this configuration is open-delta or V connection.

Y–Y: This is a configuration that is seldom used due to problems with exciting current and induced voltages.

Three-phase transformers are mostly used in the power factories and therefore investigated in this paper. Appendix E provides an illustration of the connection type.

2.2 Transformer Failures

A typical power transformer has a life expectancy of more than 30 years[7]. During this time it is obvious that such a device has several failures, thus needing maintenance to ensure that the expectancy is fulfilled. Because transformer failures are responsible for a very high amount of costs, this section is based on different studies about transformer failures. The cost side of the failures is observed in section 2.4.

William H. Bartley P.E, The Hartford Steam Boiler Inspection & Insurance Co., has done a research on 94 different cases of failures and their losses. In this study, he figured out, that in the period of 1997 to 2001 the total loss in 94 cases was over US$280,000,000[8] in the US only. This makes it clear why compensation of transformer failures is important. Apart from that, the different application types are researched and it is shown that most of the failures occur in the utility substations (38 cases). Anyway, only 6% of the loss is generated in this area. In total 36 failure cases in the step up generator area generate 70% of the total losses. Most of the total failures are insulation faults (24 failures generate a loss of about US$150,000,000). More detailed information about the HSB research is available in section 2.4.1.

Another study which was published by the CIGRE Working Group 05 [9] took another approach. In that study the failure source was attributed to the different parts in a transformer. The result was that 40% of the failures were caused by the on-load tap-changers.

The problem with investigating different studies about this topic is that their definition and characterisation of the failure groups are often different. A common denominator has therefore been sought in these studies. Apart from that, information provided by the German RWE AG[10] (German power company) is integrated in this section.

The failures are therefore separated to: winding, core, isolation, tank, bushing, oil, cooling and the load tap-changer. In this subsection, information is provided about the failures, their impacts on the transformer and typical reasons why these failures could occur. Moreover, fault trees for the different transformer parts can be found in the work of Anna Franzén and Sabina Karlsson from the Royal Institute of Technology, Stockholm[11].

2.2.1 Winding

A winding is the part of a transformer most susceptible for failures. In this area winding deformations are responsible for 12% to 15% of the transformer failures according to [12]. The reason for these deformations is often the high electrodynamics effort taking place during short circuits. Consequently, these deformations can be responsible for the occurrence of further deformations.

Typical electromagnetic forces brought together by the Hartford Steam Boiler Inspection & Insurance Co. are listed below [13]:

- Hoop (inward radial) buckling of the innermost winding
- Conductor tipping – this problem is usually associated with helical windings and continuously transposed cable (CTC). A tip over of the cable bundle caused by axial forces is tearing the paper insulation
- Conductor telescoping – typically dedicated with layer windings – excessive axial forces, will cause the individual conductors to telescope over one another.
- Spiral tightening – again, typically associated with layer windings – excessive radial forces that tighten the winding. It is evidenced by a spiral movement or shifting of the key spacers over the entire height of the winding.
- End-ring crushing – if winding's axial forces exceed the mechanical strength of the radial end ring at the bottom of the winding, it results in mechanical instability of the entire winding.
- Failure of the coil clamping system – a large sudden increase of the current flow can spread the winding coils apart axially. Because of a failure in the clamping system the restraining force is absent and consequently the coils will spread apart which results in a deformation of the coil and an immediate electrical failure.
- Displacement of a transformer's incoming and outgoing leads – connection leads or the lead supports can break in the area where they leave the windings.

Because of this, it is necessary to detect this deformation early to prevent further damages. Apart from that, winding deformations can occur because of transportation progresses.

Furthermore the ageing of the isolation has effects on the strength of the winding. More detailed information about that can be found in the isolation section 2.2.3.

Unfortunately it is hard to determine how much money is lost because of failures in the winding directly. According to the paper of V. Sokolov[14] short circuits are mostly responsible for winding failures. It is also possible that an error in some other areas can have influences on the winding. This is also clear from the examination of the different fault protocols provided through the German[10] RWE-Group. The different failure entries show that eight failures are categorised as winding failures. Unfortunately, entries in failure databases are often voluntary and consequently only a small amount of failures can be found in it. Only one case shows that the reason for a failure in the transformer winding is caused by a defect in the cooling system. In this case the transformer was used for one year in a different facility where the cooling system was polluted. This results in a raise of the solute gases and thereupon in different discharge labels. The other entries very often suggest short circuits as failures but they do not mention why it is caused. For more information, [11] provides the fault trees of the winding.

2.2.2 Core

The transformer core is carrying the magnetic flux[4]. In this task it is very robust but an error could occur during the construction, or through a transportation progress. Apart from that, the maintenance, if necessary, requires the removal of oil and the isolation. This again is not recommended, because the failure risk increases through this process. The aging progress of the core is negligible in comparison to the other transformer parts. If there is really a failure in the core, it becomes normally visible through a hotspot and is therefore more or less easily diagnosable.

2.2.3 Isolation

Another issue could be the isolation paper which is wrapped around the winding [10, 15, 16]. This paper is made of cellulose and consists of glucose chains. If the cellulose is exposed a thermal overstressing (>105 °C) the polymer chain begins to break. This expands if the temperature exceeds 300 °C and results in a total decomposition with water (H_2O) and carbon (CO_2, CO) as residue. Likewise, some carbon gases and furan derivates occur and can be disposed during the gas analysis.

The degree of polymerisation (DP) is therefore a quantity to discuss the quality of the paper. This DP value says something about the average number of glucose units per molecular chain. New papers normally have a DP value of 1200-1400[10]. With the rise of the temperature, the aging of the paper is therefore enforced. Apart from that the process is accelerated about three times if O_2 is in the process and about 8-10 times if the concentration of H_2O is higher than 2%. If the DP value is smaller than 200, it is generally said that the paper is not able to withstand shortcuts or mechanical forces anymore. Therefore it is important to know the DP value of the cellulose.

If the quality of the isolation is going down it often results in short-circuits. As mentioned before, the isolation is wrapped around the winding and therefore it is obligatory to have a good isolation for a high fault protection.

2.2.4 Tank

The transformer tank is the container of all the parts inside a transformer[6]. It protects these parts from external influences and damages. It carries the oil and should therefore be checked for leakage and corrosion. Besides that a transformer tank could be damaged during transportation. Another risk for the tank is the previously mentioned forces during short circuits. These short circuits often result in high forces, as already mentioned in the winding section 2.2.1, which can deform the tank as can be seen in Figure 2-2.

Figure 2-2: Transfomer buckling after short circuit (source RWE[10])

According to experienced data [10] of the German RWE, a massive deformation of a tank often resulted in a total breakdown of a transformer. Consequently the last solution is the scrapping of the transformer.

2.2.5 Bushings

The bushings are responsible to connect the inside of the transformer with the outside and to isolate the winding from the tank. Therefore they are designed to even withstand overvoltage and fault currents.

In this area there are two common different bushing types[3, 11]. The first one is the solid bushing which has a central conductor and epoxy-insulators or porcelain at the end. These bushings are used in all sorts of transformers. The other type of bushings is called capacitance-graded bushings which are mostly used for voltages > 25kV.

Typical failure causes include pollution and moisture. This can result in isolation failures. Apart from external forces (movements, e.g. in earthquake risked areas), sometimes even sabotage (e.g. stone throwing) could affect the bushing. Aging or overheating have effects on a bushing too. This is a reason why the condition of the bushings should be checked regularly. As a consequence of a bushing failure, it is even possible that additional transformers close to the affected one are damaged.

2.2.6 Oil & cooling system

The oil and cooler part are responsible for cooling the transformer during its work to bring it to optimal working conditions[11]. Because of that, both properties are considered together. The transformer could fail if the cooler cannot cool the equipment. This could happen because of a non-functioning cooling element or circulation not happening. Therefore it is important to check if the different pumping systems are working correctly. Another failure could occur because of the secondary cooling system (oil or water).

The oil not circulating properly again has influences on the isolation. As already mentioned in section 2.2.3 this affects the isolation paper and in turn it affects the aging process of the oil.

Because the oil is important in the isolation task it is necessary to check if this product is of high quality. The quality of the oil decreases during the aging progress of the transformer. It is usually of good quality if the transformer is new but during the aging process, moisture and oxygen reduce the isolation functionality of the transformer. If this happens, it can result in a short circuit which can damage other parts of the transformer or at least accelerate the aging progress. More detailed information about the oil can be found in the diagnostic chapter 2.3.2 and in detail in the ASTM standards.

The different standards are shown in the table below.

Table 2-1: ASTM Standards [17]

Table IV. Insulating Oil Tests		
Type of Test	**ASTM Method**	**Significance/Effects**
Dielectric Breakdown	D877, D1816	Moisture, particles, cellulose fibres/lower dielectric strength
Neutralization Number	D644, D974	Acidic products from oil oxidation/ sludge, corrosion
Interfacial Tension (IFT)	D971	Presence of polar contaminants, acids, solvents, varnish
Colour	D1500	Darkening indicates contamination or deterioration
Water Content	D1533	Excessive paper decomposition/lower dielectric strength
Power Factor	D924 (100, 25 C)	Dissolved metals, peroxides, acids, salts/overheating
Oxidation Inhibitor (DBPC[1])	D2668, D1473	Low levels results in accelerated oil aging
Metals in Oil		Indicative of pump wear, arcing or sparking with metal

[1] DBPC— Di Butyl Para Cresol

The figure below shows the different colours of oil after the ASTM standard. Dark oil indicates a deterioration of the isolation properties. The aging is indicated by the smell getting worse.

Figure 2-3: Example oil colours for a regeneration (Source ABB)

Generally, moisture and pollution promote the occurrence of failures in connection with the oil in almost the same manner as a non-functional cooling system or one with bad circulation. Therefore it is important to make sure that the active parts of the cooling system like fans and pumps are working properly and that a potential breakdown of these elements is taken account in the diagnostics.

2.2.7 Load Tap-Changer

The load tap-changer is one of the most important and susceptible parts of a power transformer. It has the task to regulate the voltage level by adding or subtracting turns without interrupting the load current. A principle function of a tap-changer is provided in [18]. It is the only direct element of a transformer which has moving parts and this is one of the reasons why a tap-changer is highly susceptible for failures. According to CIGRE Workgroup[9], units with a load tap-changer have failure origins of up to 40% in the tap-changer.

In general, there are two different types of failure in the tap-changer. The first failure occurs in the tap-selector. If there is overstressing of the material, mechanical damage can occur and consequently the tap-selector cannot change taps anymore. This malfunction can result into sparking or overheating.

If an error occurs in the diverter switch, a short-circuit can even affect other parts of the transformer. This is caused by old oil or other aged components. Therefore it is important to know the actual condition of the tap load-changer. More information about this is provided in the diagnostic section 2.3.1.

It has to be mentioned that the area in which the transformer is used makes a difference. According to RWE the tap-changer failures are significantly higher in transformers that operate in the network than in a power plant factory because of the higher amount of switching operations. If a transformer is undergoing renovation at the manufacturer, the tap-changer should be changed anyway.

2.3 Maintenance and Diagnostics

The most important to avoid transformer failures is good maintenance. For the fact that this point is a high economic issue, the trend in the last years has changed from time-based to condition-based maintenance. The key for this is a good diagnostic of the different parts to recognise failures before they occur or at least before they do considerable damage to the equipments. Therefore the different companies dealing with transformers and producing them have upgraded their systems with high quality monitoring systems. It is fundamental to know the quality of a device if condition-based maintenance should be economic. In this area there are several online and offline test possibilities that give the operator a hint if maintenance is necessary.

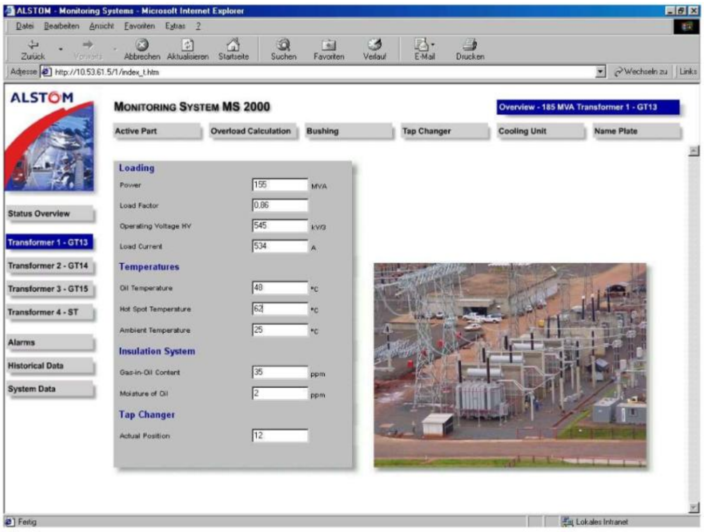
Therefore these next sections deal with the requirements and the possibilities of maintenance and diagnostic systems.

2.3.1 System requirements

A diagnostic system for a transformer should always be built in modular way[19]. This is important so that afterwards other parts of the transformer which need to be monitored can be expanded. Another factor to consider is that diagnostic system should not affect the transformer operations. Even if the diagnostic system breaks down the transformer needs to stay in operation mode. Taking this into account a plausibility control of the different measurement values could be integrated.

Apart from that a monitoring system should be dimensioned in a way that possible strategic points are controlled. Therefore the systems exist out of different modules like sensors, signal converters (A/D Converter), data communication systems (Ethernet, field bus, cooper cable, optic fibre ...), processors and signal annunciators.

Figure 2-4: Picture MS 2000 used by Alstom



A system that could solve all the different requirements could be for example the AREVA MS 3000 (see Figure 2-4 for picture of MS 2000). This system brings different possibilities to the operators, which allow them to store data, make simulations or generate reports from it. But this system only provides the processing of the data. The different sensors used to record the information have to be chosen by the operator of the transformer.

Therefore, Table 2-2 provides an example configuration, which could be an indication of how many sensors should be placed on which part of the transformer. This table is only for orientation and has to be adapted according to the requirements of the operator and the transformer.

Table 2-2: Sensor configuration often used by RWE[10]

	Sensor	< 100 MVA	> 100 MVA
Bushings	operating-/overvoltage	1	3
	Operating current and over-currents	1	3
	Oil pressure	-	3
Active component / tank	Oil temperature	1	1
	Gas in oil concentration	1	1
	Oil moisture	2	2
On load tap changer	Switch setting	1	1
	Power input motor drive	1	1
	Oil temperature	-	1
Cooling system	Operating state of pumps and fans	8	8
	Inlet-/Outlet temperature of the oil	-	8
	Air outlet temperature	-	4
	Environmental temperature	2	1
Expander	Oil level	-	2
	Humidity	-	2

Sensors

Sensors convert chemical or physical characteristics into electrical signals. The sensors are categorised in active and passive ones. Active sensors do not need an auxiliary supply, but it is only able to show a change in the measurement and not in the absolute value. If this is not satisfactory, an active sensor which operates with an auxiliary supply has to be chosen to show the static value of the measurement.

Bushings

It is important to know the different operation voltages on the different bushings. These are captured by capacitive voltage sensors. Because of this overvoltage and transient overvoltage can be easily detected. It could be also useful to know the length of the overvoltage to provide afterwards an easier diagnostic if any damage occurs.

Active part/ tank

Because of a general measurement of the load current and the operating voltage theses values could be used to infer on the aging process of the winding insulation. Moreover IEC 60354[20] describes how to identify the hotspot temperature without direct measurements. In this method the oil temperature and the current is used to conclude onto the hotspot temperature.

The constant oil temperature is not only important for the hotspot temperature that has a direct influence on the aging of the transformer; it is also important to avoid the generation of condense water through breathing. It is important to be aware about the maximal duration of an overload and how it suits the transformer.

If the cooling system is also integrated in the monitoring, it is possible to draw conclusions of the mentioned values and use them to control the cooling system. This can have direct influence on the generation of moisture. Apart from that a possible overload could be avoided by pre-cooling the transformer oil.

Winding

For the fact that winding deformation often results in vibrations, the paper of García Belén, Burgos Juan Carlos and Alonso Ángel [12] describes a model to detect these deformations. These can be measured through the tank vibrations and depend on the voltage, the current, the temperature and if it is cooled (oil pump on/off) or not. In this case, a deformation results in an increase of the 100Hz vibration harmonic. Conducting these tests during normal operation time it can help to detect failures at an early stage.

Another possibility is an offline test during maintenance. This is normally done through a frequency response analysis (FRA). In this test, a fingerprint of the transformer is made which is compared with fingerprints during former maintenance. Through the different fingerprints respectively the variation, it is possible to draw conclusions on the deformation.

Apart from that, the winding resistance could be measured to measure future possible winding deformations. For this measurement it is important to record the oil temperature since the temperature is a factor that influences the winding resistance. More information about the different possibilities can be found in the diagnostic chapter.

Isolation

The DP value or the tensile strength of the paper is not measurable while the paper is energised it is common to conduct an indirect measurement[21]. Consequently it is likely to take advantage of the fact, that during the aging progress a chemical reaction takes place which results in the disposal of derivatives of 2-furaldehyde.

These furanics are dissolved in the transformer oil and can be analysed without the need to de-energise the transformer.

This analysis describes five different derivatives (5HMF, 2FOL, 2FAL, 2ACF and 5MEF). Apart from 2FAL all other furanic components are unstable and normally degrade after several months. Nevertheless, if certifiable, the different furanic components are indicators of different possible failures.

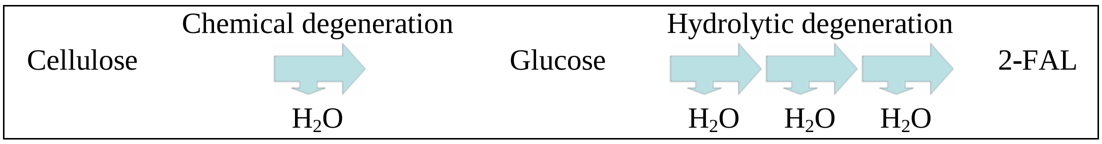
It is absolutely necessary to take into account that there is a possibility that oil maintenance reduces the furanic components and therefore the result is wrong if it is investigated separately. Consequently, these results, like others, should be seen as a trend line review and not on their own. From one result it is not possible to conclude if there are any problems with the transformer or if the transformer is at the end of its lifetime. This is an important reason why a regular maintenance and evaluation of the encountered data is so important.

A possibility to find out the DP value through the oil analysis is the „de-Pablo-Relation“[22]:

$$DP = \frac{1850}{2.3 + F}$$

In this equation, the F is the furan content in ppm.

Figure 2-5: Cellulose degeneration[10]



It is necessary to control these facts because the generation of the furanic components promote the aging influences on the oil and the isolation paper. During the chemical degeneration (see Figure 2-5) of the cellulose, one water molecule is produced and during the hydrolytic degeneration of the glucose to 2-FAL, three water molecules are produced. This, as already mentioned in chapter 2.2.3, can result in further degeneration of the isolation.

On-load tap-changer

The on-load tap-changer is subject to a high stress value and is one of the most important components of a transformer. In case of a fault it can cause damages on the transformer tank. Therefore it is useful to monitor the different switching settings and in result draw conclusions on the total amount of switching operations. Apart from that, it lets the operator know the total amount of switched currents. These values are important to determine the lifespan of the switch.

If the power consumption of the motor is also monitored, it is possible to gather information about the mechanical parts of the switch[19]. The turning moment is proportional to the power consumption and therefore a possible stiffness can be identified in time.

Online gas in oil

An online gas in oil analysis could be suggested if a transformer had several noticeable problems in the past without any possibility to change it. In this case a gas analysis instrument is connected to the transformer which takes oil samples in specified times and analyses this. Normally the sample is vented by vacuum extraction and afterwards analysed through gas chromatography, flame ionisation detector and methane ioniser[10]. The results can be used afterwards for further investigations. It is also possible to show up a trend if different results are saved. If the results of the online gas-in-oil analysis are not adequate, the results can be checked by doing an offline analysis. While the latter is not necessary, the results could be useful to control online tests during planned maintenance. Either way the online results can be useful to help change the cooling process or to do forecasts about the life of the transformer.

Apart from that it is a big advantage that the amount of offline tests can be reduced and consequently the downtimes as well. With the help of this online test results, a necessary maintenance could be better planned and sometimes conducted during the operation of the transformer.

2.3.2 Dissolved gas analysis

This section provides an overview of interpretation of the dissolved gas analysis (DGA) results. Therefore, two different methods are described to provide advice on the different failures in the transformers.

Key Gas Method

This method is established by the IEEE[23] and is based on the generation of gases inside the transformer oil. Therefore the hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and oxygen (O_2) concentration are measured and this make it possible to draw conclusions on the condition of the transformer.

All these gases are generated through the degeneration of the transformer oil itself except carbon monoxide and oxygen. O_2 and CO and CO_2 are results of the degeneration of the cellulose paper. Apart from that it is possible that the latter, nitrogen (N_2) and moisture are absorbed from the air.[23]

The IEEE has developed a four-condition criterion that makes it possible to assess the risk of failures. This criterion should only be used if no previous gas analysis is available. In other cases the previous results have to be taken into account.

The condition of the different transformers is determined by finding the highest level for the individual gases or the total dissolved combustible gas (TDCG)[23]. Therefore, it is assumed that the transformer is categorised in that condition in which the worse gas belongs to (gas or TDCG).

Table 2-3: Dissolved key gas concentration limits [µL/L (ppm)[2]]

Status	**H_2**	**CH_4**	**C_2H_2**	**C_2H_4**	**C_2H_6**	**CO**	**CO_2**	**TDCG[3]**
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101–700	121–400	2–9	51–100	66–100	351–570	2500–4000	721–1920
Condition 3	701–1800	401–1000	10–35	101–200	101–150	571–1400	4001–10000	1921–4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10000	>4630

Condition 1: Total dissolved combustible gas (TDCG) below this level indicates the transformer is operating satisfactorily. Any individual combustible gas exceeding specified levels in Table 2-3 should have additional investigation.

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[2] "The numbers shown in the table are in parts of gas per million parts of oil [µL/L (ppm)] volumetrically and are based on a large power transformer with several thousand gallons of oil. With a smaller oil volume, the same volume of gas will give a higher gas concentration. Small distribution transformers and voltage regulators may contain combustible gases because of the operation of internal expulsion fuses or load break switches. The status codes in Table 1 are also not applicable to other apparatus in which load break switches operate under oil." [23]

[3] "The TDCG value does not include CO_2, which is not a combustible gas." [23]

Condition 2: TDCG within this range indicates greater than normal combustible gas level. Any individual combustible gas exceeding specified levels in Table 2-3 should entail further investigation. A fault may be present. DGA samples are required at least often enough to calculate the amount of gas generation per day for each gas.

Condition 3: TDCG within this range indicates a high level of decomposition of cellulose insulation and/or oil. Any individual combustible gas exceeding specified levels in Table 2-3 should entail further investigation. A fault or faults are probably present. DGA samples should be taken at least often enough to calculate the amount of gas generation per day for each gas.

Condition 4: TDCG within this range indicates excessive decomposition of cellulose insulation and/or oil. Continued operation could result in failure of the transformer.

Generally it is more important to recognise sudden increases of the different gases than to observe the total amount.[24] An exception of this is acetylene C_2H_2 which is an indication for high energy arcing which results in a high temperature (>500 °C). If a rise of the C_2H_2 is diagnosed, it is important to ensure that the generation of C_2H_2 is stopped and therefore necessary to control the transformer regularly. Consequently the IEEE mentioned that a daily sample should be taken if the transformer has reached condition 4 (compare Appendix A). If the rise of C_2H_2 is not stopped, it could be necessary to take the transformer out of service to avoid damage.

A description of the generation of the different gases is given in Appendix C. This overview points out which gases are generated according to the different approximate temperatures. Furthermore, this chart was used by R.R Rogers to develop the Rogers Ratio Method[25].

Rogers Ratio Method

The Rogers Ratio Method can help analyse the problem which causes the raise of the different gases. This is the main difference to the Key Gas Method which on the other hand is used to find a problem.[24] Therefore, the Rogers Ratio Method is the second step after finding out the different values of the key gases. With these results the different ratios of

$$C_2H_2/C_2H_4 \qquad CH_4/H_2 \qquad C_2H_4/C_2H_6$$

are built. For the results Rogers presents a table (see Appendix D) with specific codes for the different gas ratios. With these codes the matching fault can be found with a description of the problem. The quality of this method depends on the amount of gas that is available for the research. The Fist3-30 report from the US Government[24] advises that this method is only reliable if the detection of the gases is at least 10 times the detection limit. (For example, see Appendix B).

The example in Table 2-4 shows how a possible result of the Rogers Ratio Method could look like. The full table with all the information to interpret the different ratios is available in Appendix D.

Table 2-4: Example Roger Ratio Method

Hydrogen (H_2)	20 ppm
Methane (CH_4)	170 ppm
Ethane (C_2H_6)	156 ppm
Ethylene (C_2H_4)	17 ppm
Acetylene (C_2H_2)	0 ppm
Carbon Monoxide (CO)	120 ppm
Carbon Dioxide (CO_2)	361 ppm
Nitrogen (N_2)	70160 ppm
Oxygen (O_2)	600 ppm

Rogers Ratio		
ratio	result	code
C_2H_2 / C_2H_4	0	0
CH_4 / H_2	8.5	2
C_2H_4 / C_2H_6	0.109	0
Fault: Thermal fault temperature range 150-300 °C (see note 3 Appendix D)		

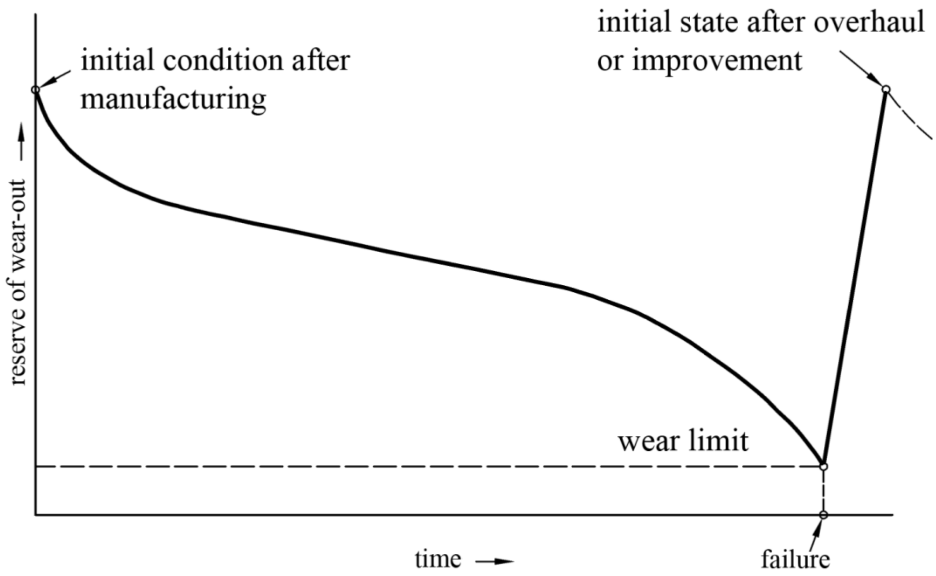
This Method is also described in IEC 60599. 42[25]

2.3.3 Maintenance versus new transformer

As mentioned before, in the past years the diagnostic and maintenance programs have made a lot of progress. Because of that, in power plant factories, the transformer faults can often be diagnosed before they occur. This results in lower maintenance costs in comparison to the years before. Power plant factories are at the beginning of the electricity chain which means that they need to ensure the consequent energy supply. This makes it necessary that spare transformers are available for possible emergencies. Another point to notice is that the average time needed for a transformer (> 100MVA) to be manufactures and delivered is two years after it has been ordered[10]. This fact alone makes it necessary to repair a transformer failure during that time. Furthermore, most of today’s transformers are connected to online monitoring programs and consequently the operator has an immediate idea of what the failure is when a problem occurs. This can be used to make decisions about the failure and future actions. If it is obvious that the transformer is not repairable during the available amount of time, a spare transformer is then used. But if this option is not available in the same power plant factory it could be possible for it to be taken from another one. According to information provided through RWE, the cost of repairs for nearly every transformer failure is up to 70% of the costs of buying a new transformer. However it is not possible to make a general statement on actions taken in case of failure. If no spare transformers are available, this amount mentioned above could possibly rise.

For the fact, that the principles of the transformers are still the same as centuries ago, the condition of a transformer can be set back to its initial condition through overhaul procedures or by making improvements. Figure 2-6 shows the reserve of wear-out and its regeneration.

Figure 2-6: Reduction of reserve of wear-out and afterwards regeneration



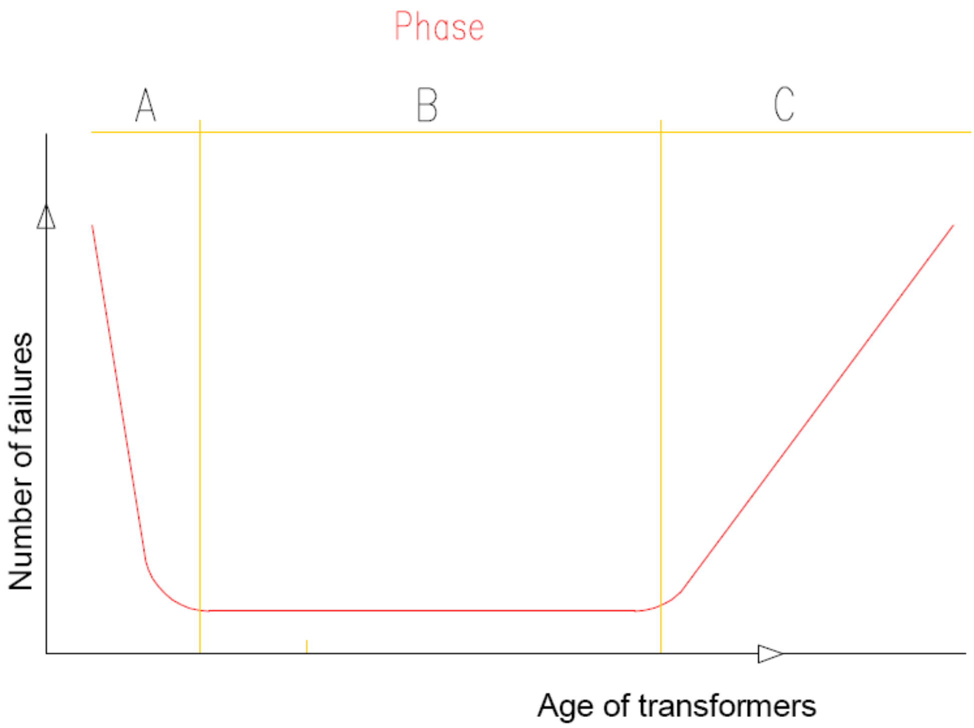
RWE states that the average transformer generates an amount of 20-35% of maintenance costs during its whole life in comparison to its purchase price. This amount can vary in other plants if the monitoring/maintenance programs are different. In some cases, even a functional old transformer can be scrapped if too many spare transformers are available. This becomes economical in the last years because of the high rise of prices for raw materials and because of limited amount of space. Therefore some transformers are sold to specialist for scrapping of transformers.

2.4 Transformer costs

2.4.1 Failure Rate

In this section, the costs of the different transformer failures are researched and summarised. As already mentioned the transformers have a lifetime span of about 30 years. However, the technical lifetime of a transformer could be much longer than that. For example, the German RWE has transformers in their power plant factories, which are operating since 56 years and are expected to keep running in the next years. In general, the chance for a transformer failure is very high at the beginning of its life and at the end. This is visible in the bathtub curve which is shown in Figure 2-7.

Figure 2-7: Bathtub Curve by Georg Daemisch[26]



The figure shows that transformers in their first 1-3 years are more vulnerable to failures than in their midlife. According to Daemisch[26] the reasons for these failures are mostly caused by construction or design errors (zone A). The failures that occur in the first years are mostly repaired on warranty of the manufacturer. These costs can sometimes be as high as a new transformer would cost. The second phase (zone B) which could be up to 30 years is normal operation mode, with a small amount of failures. After this time, (zone C) a transformer is very vulnerable because of aging failures, which can be seen in the increase of the failure curve. The amount of time after which a transformer comes into zone C depends on the maintenance efforts of the operator. Concerning the study of the Hartford Steam Boiler Inspection & Insurance Company[27], the average age for a failure was 18 years in the researched transformers between 1997 and 2001.

This study shows clearly the difficulty of getting representative data to study the costs of the failures. The insurance company, Hayward Steam Boiler has requested information about losses to worldwide delegations for the years 1997 and 2001 so that they can analyse. 94 cases were submitted. In some cases the contributors[27] were not even able to identify the age of the transformers. Therefore, this data could not be used in the study. Apart from that the German "transformer failure data base" (internal database of a head organisation for the power grip) is filled with limited information, because the different companies are afraid of being penalised for cartel agreements. This shows how difficult it could be to gather information for such types of research.

Unfortunately, the RWE group was not willing to give internal commercial data to an outstanding person. Therefore only the Internet and library database were available.

The table below is adapted from the research of the 94 transformers by the Hartford Steam Boilder Inspection & Insurance Company. [27]

Table 2-5: Cause of Failures by Hartford Steam Boilder Inspection & Insurance Company

Cause of Failure	Number	Total paid
Insulation Failure	24	$149,967,277
Design /Material /Workmanship	22	$ 64,696,051
Unknown	15	$ 29,776,245
Oil Contamination	4	$ 11,836,367
Overloading	5	$ 8,568,768
Fire /Explosion	3	$ 8,045,771
Line Surge	4	$ 4,959,691
Improper Maintenance /Operation	5	$ 3,518,783
Flood	2	$ 2,240,198
Loose Connection	6	$ 2,186,725
Lightning	3	$ 657,935
Moisture	1	$ 175,000
Total	94	$ 286,628,811

The first group describes **insulation failure** which was the leading failure in the HSB study. The failure factors for this failure are pyrolosis (heat), oxidation, acidity, and moisture but the latter was reported separately.

As a second group, HSB defines **design /manufacturing errors**, which includes loose or unsupported leads, loose blocking, poor brazing, inadequate core insulation, inferior short circuit strength, and foreign objects left in the tank.

The **oil contamination** group includes sludging and carbon tracking.

Overloading includes the failures caused by a load that exceeded the nameplate capacity.

The next group called **fire /explosion** is about a fire or an explosion outside a transformer which results into a failure. This group has nothing to do with internal failures which cause fires or explosions.

After that, the **line surge** group includes switching surges, voltage spikes, line faults/flashovers, and other transmission and distribution abnormalities.

The **maintenance /operation** category includes disconnected or improperly set controls, loss of coolant, accumulation of dirt and oil and corrosion. If the other overloading loose connection and moisture groups are added, this group shows problems with the maintenance. With the right diagnostic methods the warning signs of those problems should be easily detectable and consequently it should be possible to correct the failures before they occur.

In the **flood** category there is a summary of failures which are caused by man-made or natural floods.

The failures in combination with workmanship and maintenance in making electrical connections are summarised in a group called **loose connections.**

Lightning is only categorised in the **lightning** group in the event that there is confirmation for a lightning strike.

The last category that includes failures caused by leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil is called **moisture**.

HSB is an insurance company and its categorisation is mostly different to the ones which would be made by a system operator. The different system operators would very likely combine the different maintenance groups under one group for the fact that they do not have to split them under insurance options.

It also has to be mentioned that this study includes business interruptions as well. Therefore, Table 2-5 shows the real damage on the transformers and the resulting business damage.

Table 2-6: Number and amounts of losses by year

Year	Number	Total Loss	Total Property Damage	Total Business Interruption
1997	19	40,779,507	25,036,673	15,742,834
1998	25	24,932,235	24,897,114	35,121
1999	15	37,391,591	36,994,202	397,389
2000	20	150,181,779	56,858,084	93,323,695
2001	15	33,343,700	19,453,016	13,890,684
total	94	286,628,811	163,239,089	123,389,722

2.4.2 Price of a new Transformer

The price of a new transformer is very hard to determine in general especially in the area above 100MVA. In this area, the transformer is built on request and therefore the prices vary according to the requirements of the operator and its conditions with the manufacturer. A request about prices to the German RWE shows that their average cost price for transformers above 100MVA is about 10,000Euro/MVA. This would result in ~5,000,000 Euro for a 500MVA transformer. Both Siemens and ABB did not give a concrete answer to this request. They only mentioned that the price depends on the requirement that the transformer has to fulfil.

Apart from that, different models and studies give ideas on the different prices of transformers. However, most of these studies are mostly valid with prices for smaller transformers. An example is the article Transformer Life-Cycle Cost[28] which mentioned a purchase price of $10,845 for a high efficient 750kVA. As mentioned before the average price of RWE is only valid with bigger transformers.

Therefore it is recommended buying transformers with a very high efficiency. These transformers may be more expensive in its sales costs but the higher efficiency will result in savings over the transformer life. This can result in double benefits in the future, if emission saving systems are established or the existing ones (European Union) get CO_2 prices that have influence on buying decisions.

2.4.3 Cost of maintenance

The different maintenance costs depend on what is understood by maintenance. The German DIN standard DIN 31501 describes this word in general with four different categories. The first one describes general maintenance. This means that agreements are made to make sure that the transformer life is expanded. An example could be the change of the cooling liquid because of pollution. This maintenance type should be done on every device. The next category is about determination of the status quo and includes the reason for the current status. Depending on the work that should be done this category is obligatory for maintenance as well. Before specific work can be done, it is often necessary to know the failure or the reason for it. Apart from that, it is often necessary to overhaul a device if it is broken. This procedure is described as a job of its own as long it does not include any improvements. Improvements are implemented to make a device more efficient than before. An example would be the expansion of a monitoring system to an old transformer.

Depending on the different actions that are made the costs can vary. Apart from that it depends on detailed circumstances to give a detailed overview of all transformers. Generally it is accepted [29] that a preventive maintenance program, which is for example based on the results of an online monitoring system, can help save money in contrast to a lasting program which only repairs failures. But RWE mentioned cases where a transformer type was not maintained anymore because it was decided that this type should be rejected if a failure occurs. Therefore it depends on the specific transformers and the corporate-policy decision of what has to be done. In another case a defect transformer was not repaired although it was not on the end of its lifetime or had an irreparable defect. In that case the reason for the scrapping was just a space problem. There have been several other spare-transformers from the same type and RWE could get a good price because of high resource prices.

Moreover, Glenn Swift and Tom Molinski [30] have made research to simply overload transformers. Their assumption is based on the fact, that the technological lifetime is longer than the economical lifetime. In combination with DGA and other mentioned monitoring possibilities, they come to the conclusion that it is more efficient to overload existing transformers – even if they possibly fail – than to install bigger transformers. Nevertheless, they mention that the following policy results depend on the short-term or emergency overload capabilities of existing transformers.

This shows that there are many different possibilities to save money during maintenance and that general statements are very difficult. It depends on the technical possibilities that the operator has and on the willingness to take risks.

2.5 Summary

Transformer maintenance cost diversifies with the amount of service the operators want to do. It is generally accepted, that condition-based maintenance in the power transformer area saves money, even if the monitoring equipment, generates costs. Because it can take up to years for a new transformer to be ready, the operators sometimes have no other choice than to repair the existing one even if it would be cheaper to buy a new one.

Consequently the operators have to find their middle way between saving money and reliability. Failures can always occur and nobody can provide a 100% guarantee against that. But the operators have to decide what is compatible with their needs and their customers and try to guarantee this through a maintenance program that is caters to these needs. In the case where the operator has spare transformers he would probably be willing to pay less money on maintenance of the existing ones because in failure cases the spare transformers can be used instead.

Therefore, it is important that the operator knows the condition of all its transformers of the same type and makes plans for investing in new ones before failures occur.

3. SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT (SMES)

3.1 SMES

3.1.1 Technical Description

A superconducting magnetic energy storage (SMES) unit is a device that is able to store electrical energy. It stores energy without changing it to other energy forms as mechanical or chemical. The idea was to load the SMES units during off-peak times and discharge it in peak times like other storage systems but with a very high efficiency (~97%)[31]. Historically the SMES concept goes back to Ferrier (1969) in France and the decades after several research programs were established around the world.

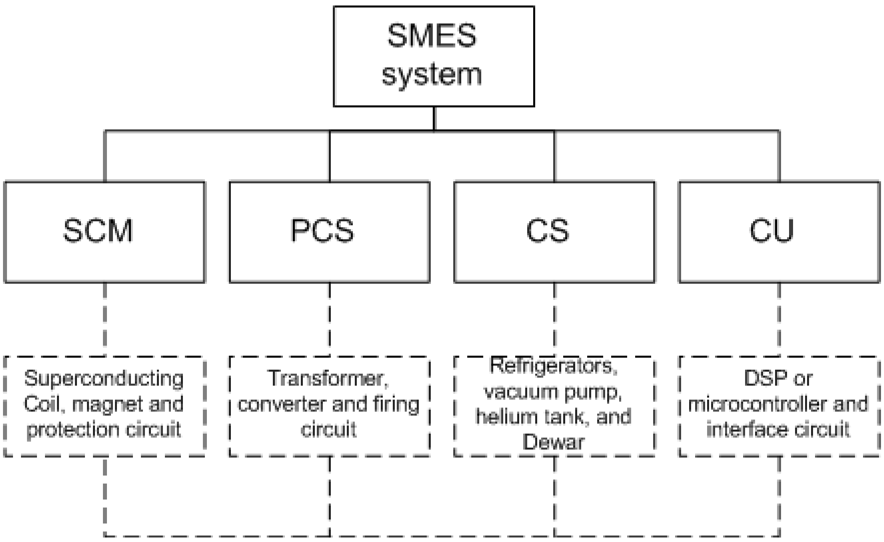
A SMES unit stores the energy directly as an electric current passing through an inductor. In this conductor (coil), the current circulates indefinitely and for the fact that it is made of superconducting material, it can operate nearly without any loss.[31] To achieve this it is necessary to cool the conductor cryptogenic to make it a superconductor, which has no resistive losses.

Generally, a SMES system exists out of four different parts, which are the superconducting coil with the magnet (SCM), the power conditioning system (PCS), the cryogenic system (CS), and the control unit (CU).[32] The different functions are described below and available in Figure 3-1.

SCM: The SCM is used to store the dc-energy and exists out of the superconducting coil, magnet and the coil protection. Therefore, the coil and the magnet need to be strong enough to withstand the Lorentz forces. The coil protection is also necessary to make sure that the coil is protected against failures, which could result in several damages to the SMES System.

PCS: This system contains firing circuits and converters. It is the connecting system between ac utility and SCM and it is also responsible to convert the ac electrical energy to the dc electrical energy, which is stored in the SCM. Its task is also to convert the stored dc energy back to ac in case of an energy request.

Figure 3-1: Block diagram of SMES[32]



CS: The cooling system is required to keep the SCM on its operational temperature. Therefore, it exists out of refrigerators, vacuum pumps, helium tank and pipes and a dewar.

CU: The major part of a SMES unit is the control unit. The CU controls the different functions and the protection of the coil. It also performs the different operations and exists generally out of a microcontroller or a DSP.

With the discovery of high temperature conducting materials in 1987, some improvements in the SMES area were expected. In contrast to a low-temperature conducting coil (LTS) which operates at about 5 °K, a high-temperature conducting coil (HTS) has an operation temperature of about 70 °K. This again results in savings in the cooling system, which according to Wei-Jen Lee and Chung-Shih Hsu [33] is around 15% of the capital costs. They mention that nearly 40% of the operation costs have to do with cooling and therefore the use of a high-temperature conducting coil is able to save a lot of money. Depending on the size of the SMES unit, the cooling progress to operation temperature is much faster with a HTS coil in comparison to a LTS one. Lee and Hsu [33] state that it takes 1600 hours to bring the systems from 300°K to 100°K and further 1900 hours to bring it from 100°K to 4°K. This shows clearly the time and cost savings if the device would work on a temperature around 70°K. A problem in this case may be the fact that according to Dr. Krischel [34] HTS materials are still much more expensive than LTS ones. Nevertheless today's research project goes more and more in the HTS direction. For the sake of research the Florida State University undertook the project of building a SMES unit. This project was aborted after several years of preparation and building progress. According to Dr. Michael Steurer (Florida State University) this results from the fact that today "nobody is using Low-Tc SMES technology anymore"[4].

[4] Mail from 24.May.2009

3.1.2 Application areas

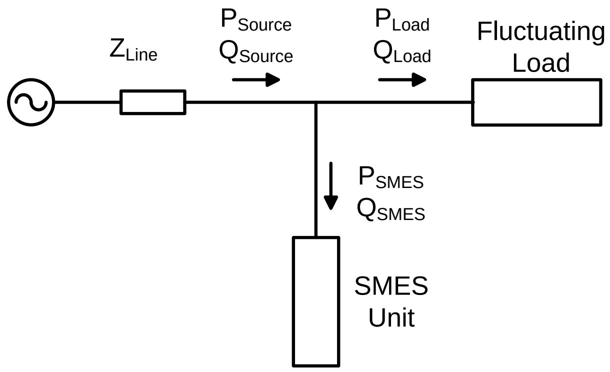
Different market areas have different requirements for the energy storage technologies. Therefore this section describes the needs a SMES unit can possible fulfil.

A SMES unit can be designed to provide different services to the network. The main differences are if a system is used to improve power system stability or to advance power quality.[32] Therefore the SMES units can be used to improve the power system quality by filtering oscillations of a small frequency. This is possible because of the ability to modulate real power and the reactive power. Apart from that voltage instabilities can be absorbed by SMES units because of the energy storage capability. In that time other generators or power sources can be started to compensate the instability.

Another application area is if the SMES unit provides spinning reserves for major transmission lines. In general it is common that around 7%[35] of the maximal load which is caused by the system is held back in reserve. This could possibly be a SMES system because of the fact that it has the ability to store a high amount of energy. In this reserve time, gas turbine can be started to provide a normal service. The SMES unit can be much more efficient than other available technologies.

The third area is to let SMES units manage the load fluctuations[32]. This means that a SMES unit is connected between the source and a fluctuation load like shown below in Figure 3-2.

Figure 3-2: A typical power control system with an SMES unit to balance a fluctuating load[32]



As a result a possible power fluctuation will be cleared by the SMES unit. If the power is described through the following equations,

$$P_{Load} = P_{Lc} + \Delta P_{Lf}$$

$$Q_{Load} = Q_{Lc} + \Delta Q_{Lf}$$

with ΔP_{Lf} and ΔQ_{Lf} as the fluctuation, then the SMES unit has to provide the following components:

$$P_{SMES} = -\Delta P_{Lf}$$

$$Q_{SMES} = -\Delta Q_{Lf}$$

This prevents the fluctuation from being present in the source line as well. The control of the power can be used in utility control areas to make sure that the load between the transformers is stable. If generators are ramped up in control and ramped down in the receiving area, this can result in an area control error. A SMES can prevent or reduce this type of error which results in a more efficient generation[32].

Apart from that a SMES unit was originally thought for load leveling applications by Ferrier[33]. As already mentioned, the energy should be produced in the off peak times and stored in the SMES Unit. In the peak time the stored energy is released from the SMES unit and provided to the system. From an economical point of view this is called the conversion of low-cost energy to higher value energy.

Besides these, SMES can also help to isolate critical loads from the system. Examples can be found in the paper industry or in military loads. In this area it is necessary to make sure that different machines are protected from variations. Because a SMES unit has a very fast response time, it is the optimal device to separate these critical loads from errors that occur in the network, like lightning strikes or flashovers. Several papers [36, 37, 38, 39] provide more information on this topic. There are two different methods to protect the load from the rest of the system. The first method consists of protecting all the loads together (Figure 3-3) whereas the second method focuses on protecting the more decentralised loads separately (Figure 3-4). [32].

Figure 3-3: SMES system for defending all critical bus loads[32]

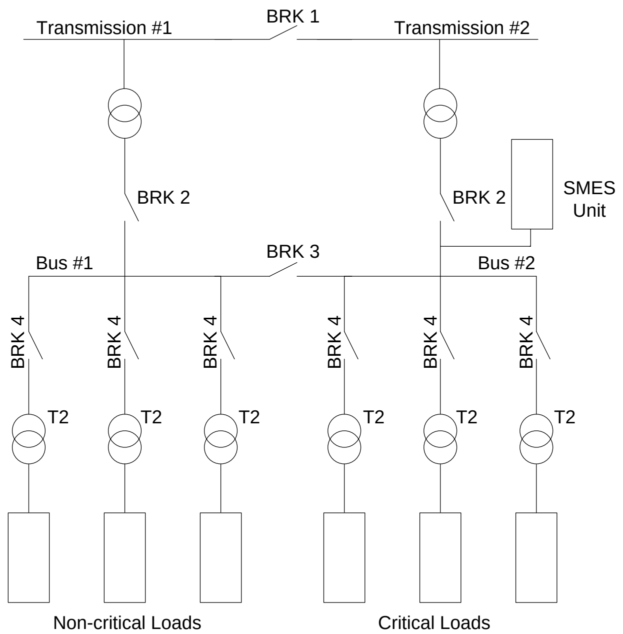


Figure 3-4: SMES system for defending distributed critical loads[32]

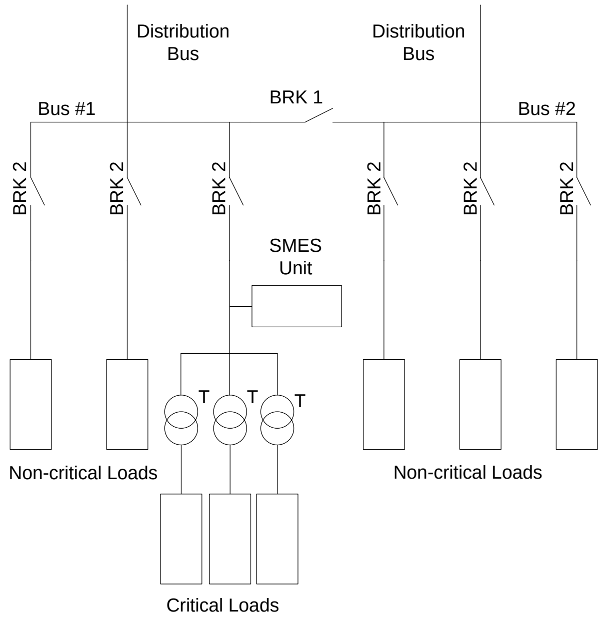
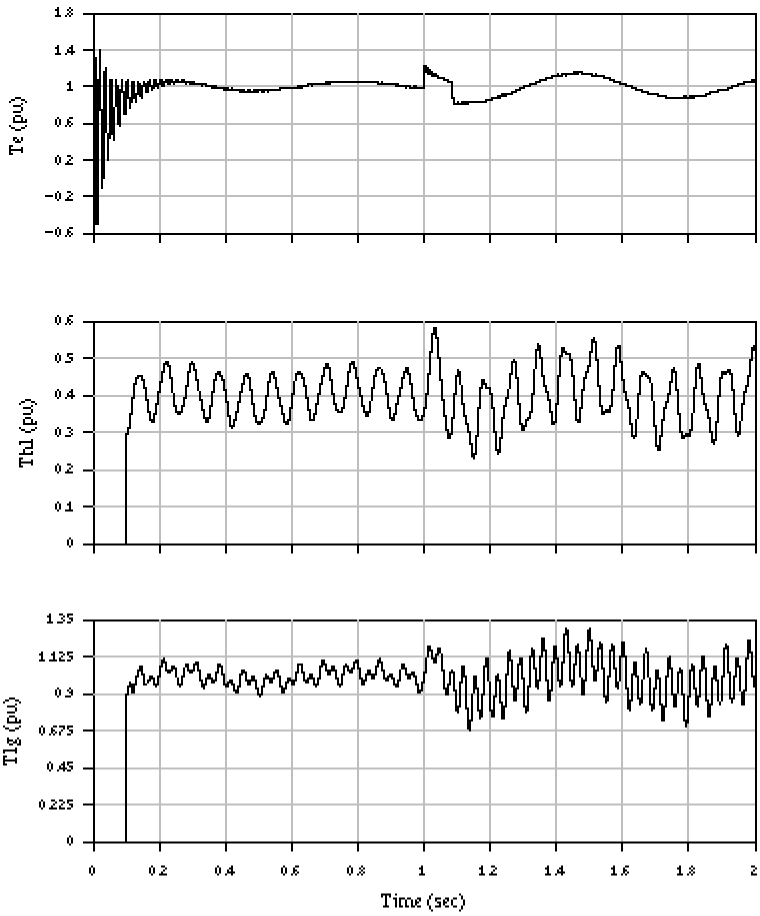
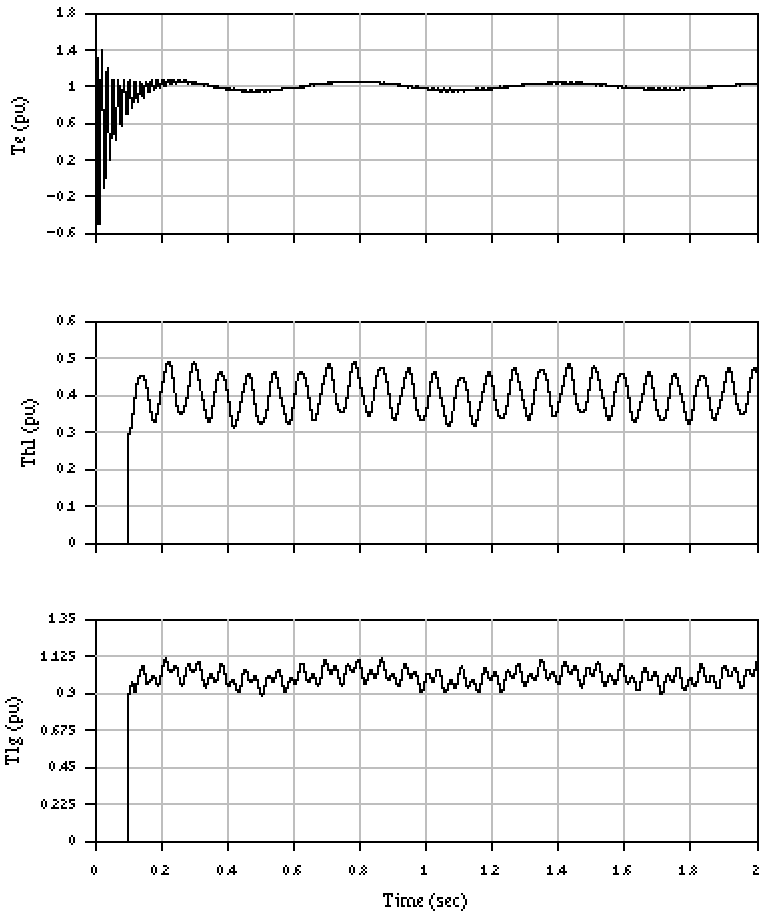


Figure 3-5: System performance under small disturbance (without SMES) [40]



However it can be also necessary to protect normal devices. An example could be a generator which is protected by a SMES unit to minimise influences of forces on changes in the step load. Figure 3-5 and Figure 3-6 show the different of torsional forces on the mechanical shaft for a system without and with SMES protection. In that example “a disturbance at t=1 sec is given for a duration of 5 cycles”[40].

Figure 3-6: System performance under small disturbance (with SMES)[40]

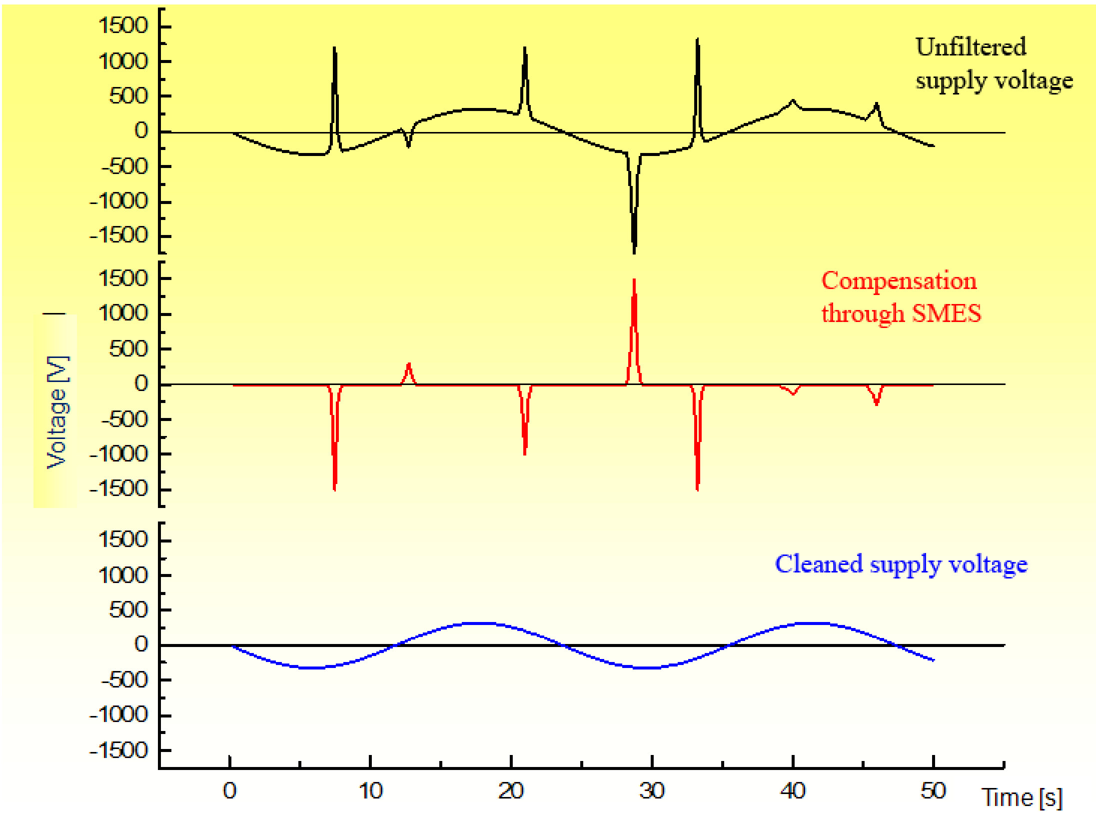


Depending on the application it can be necessary to have an uninterruptible power supply (UPS). A SMES unit can be used for this task and it can obviously be more effective than other technologies. An example for such a device has been designed and built by the ACCEL Instruments GmbH [41] or by Chu and coworkers [42].

Apart from this task, it is possible to use a SMES unit to balance voltage asymmetries. According to Xue and coworkers[32] asymmetrical voltages will decrease the efficiency of the transformer and transmission line, decrease the output power of transformer, reduce the efficiency of motors, affect the operation of critical load and even endanger the safety of equipment. Therefore it is obvious that minimising asymmetrical voltages can increase the efficiency of the whole transmission system.

The mentioned regulation is shown in the example in Figure 3-7.

Figure 3-7: Cleaned supply voltage with the help of a SMES Unit[43]



3.2 Other comparable technologies

3.2.1 Introduction

The problem with electrical energy is that it normally has to be produced at the time it is needed by the different customers. During night-time less energy is needed and power plants have to work below their optimal efficiency. Consequently different people have thought about the idea of the different possibilities to store energy in off peaks to release it again during peak times. Therefore it is common to describe the different systems as electrical energy storage (EES) technologies. Furthermore there are subcategories to describe the technical aspects of the EES. These are: electrical energy storage, mechanical energy storage, chemical energy storage and thermal energy storage. This section deals with other available technologies and how they work.

3.2.2 Flywheel

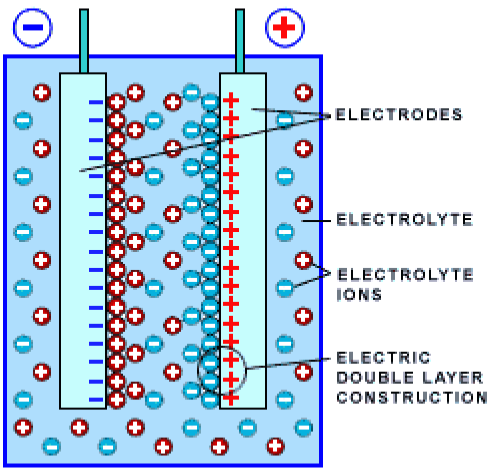
The flywheel technology is one of the oldest energy storage technologies. The energy is stored by accelerating a rotor up to a very high rate of speed and maintaining the energy in the system as kinetic energy[44]. This technology belongs to the mechanical energy storage. Nowadays, the system consists of an electric motor to spin the rotor during charge and the same one is used during discharge as a generator. To minimise losses, to protect the rotor and to achieve maximum storage of kinetic energy, the flywheel spins at a very high velocity in a vacuum housing. With these improvements and loss reduction in the last years it is possible to reach efficiency of up to 90% [31]. An advantage to other technologies is the long life capable of providing hundreds of thousands of discharge-charge cycles. Generally flywheels can be used for optimising power or energy. If it is used for power optimisation, the main focus is normally on the motor/generator and power electronic whereas energy applications have more requirements for a larger high speed rotor. Therefore the first application runs with a speed of up to 10000 RPM and has a steel rotor. In the high-speed variant it is often common to have fibre glass or carbon fibres impregnated in an epoxy and wound into a thick cylinder. [44] This application runs in a range from 20000 to 60000 RPM.

Flywheels are used in power quality, regenerative energy and frequency control. But as mentioned before the different designs for the different requirements often make it impossible to use one flywheel for other application areas. Nevertheless, a flywheel, in comparison to other technologies, has a relatively low need for space and lifetime costs but can only used for short-term applications (~10-100 sec)[31].

3.2.3 Electrochemical Capacitors[44]

A capacitor is made up of two electrodes that are separated through a dielectric. In terms of energy and power performance, these devices operate similarly to rechargeable batteries and electrolytic capacitors. Electrochemical capacitors differ from batteries in the sense that they do not store energy in redox reactions that occur in the electrode structure. Electrochemical capacitors store energy through electrostatic interactions that occur in the electrode and solution interface region, also known as the double layer[1]. An electrochemical capacitor has the energy storage capacities of a battery and the operation characteristics of a capacitor.[44] Because the capacity of capacitors is directly related to the surface area of the electrode, the ability to storage energy increases with the square of the applied voltage. During charging, when the electrode is polarised, nearly half of the electrolyte material transfers electron to the other half. These ions migrate to the opposite charged electrode as shown in Figure 3-8 and build a charged layer on the surface without exchanging electrons. Electrochemical capacitors are often called supercapacitors, ultracapacitors or electric double layer capacitors, even if these terms are company trademarks.

Figure 3-8: Eletrochemical Capacitors [1]



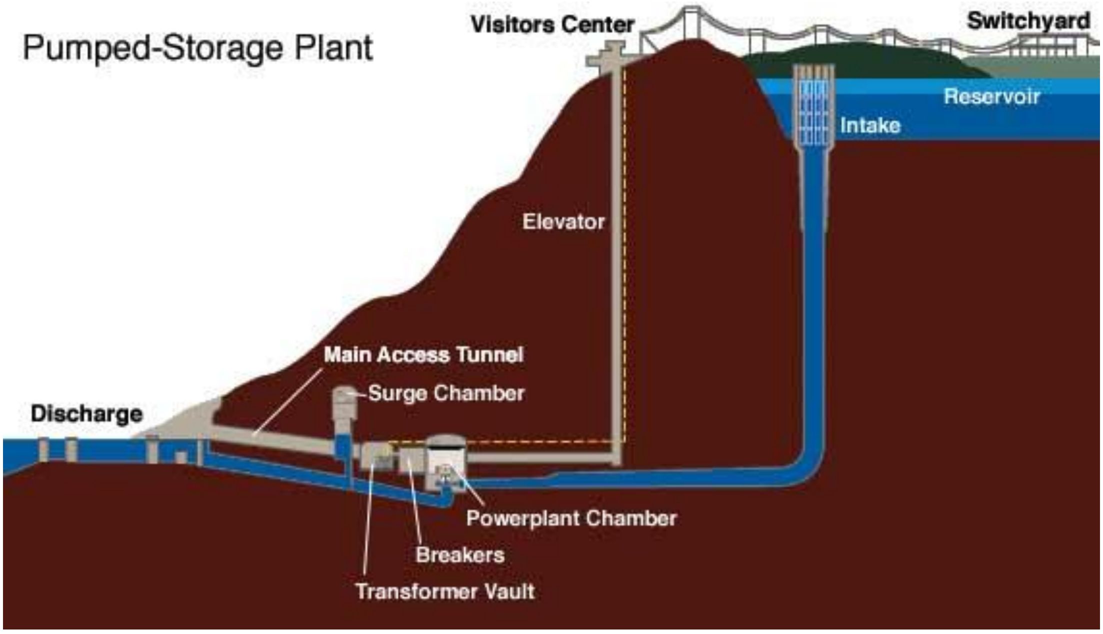
The quick response of electrochemical capacitors and their reliability at full power are a few key facts why they are used in the retailer market. They can operate in a wide temperature range from -50°C up to 85°C. The average DC-DC round trip efficiency is between 80% and 95% during normal operations.[44]

One of the biggest advantages in comparison to other technologies is the lack of moving parts or chemical reactions. Therefore electrochemical capacitors are capable of hundreds of thousands of charge/discharged cycles [44].

3.2.4 Pumped Hydroelectric Storage (PHS)

A pumped hydroelectric storage also called PHS is a technology which was first used in the 1890s in Switzerland and Italy[31]. This technology is able to store large energy by using two different reservoirs located in different elevations. Between both those reservoirs, a connection is used to pump up water if energy is stored, and released through a turbine if energy is needed (discharge). The schematic is shown in Figure 3-9.

Figure 3-9: Schematic diagram of PHS [45]

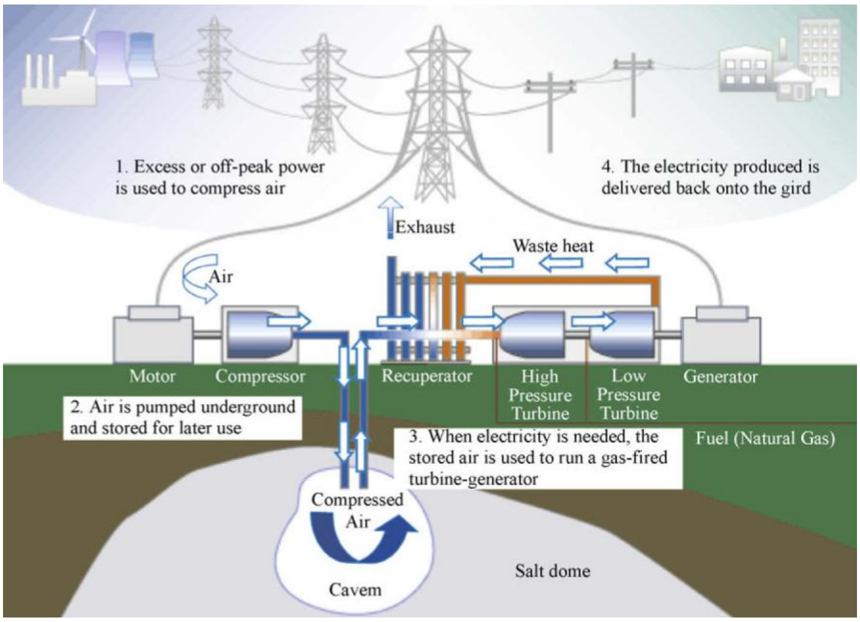


The average rating of such devices is around 1000MW and every year around 5GW are newly installed. Because of the fact that two reservoirs have to be built or made available, it is not possibly to install a PHS on any place. In this case, it is important to take a few factors into account: the environment, the building time and the high costs. In total it can be said that because of transformation and losses, the efficiency of a PHS is around 71-85%[31].

3.2.5 Compressed air energy storage (CAES)

Like the PHS, the CAES is the only technology which is currently available and could be mentioned as a large-scale EES. A CAES system is used to compress air during off-peak times and to store these in an underground reservoir. In the peak times during the day, this air is released and used to power a gas turbine to produce energy. A schematic overview over the technology of CAES systems is provided in Figure 3-10.

Figure 3-10: Schematic diagram of CAES [31]



The technology goes back up to 1978 when the first CAES facility was built in Germany and is still in operation. Today only two facilities are in operation. The German one can generate 290 MV for up to four hours.[44] The other one, located in Alabama, USA, can provide 100MW for about 26 hours because of a bigger cavern. It is more efficient than the German one because of several improvements. It went online in 1991 and has therefore 13 years of development ahead. The CAES technology have less building costs in comparison to a PHS because of the use of existing underground caverns. This results in a KW price depending on the underground storage condition between $400 and $800 per KW. Today several projects are in planning or building phase all around the world.

3.2.6 Thermal energy Storage

Thermal energy storage (TES) goes another way: energy in this instance is normally not brought back in electrical form. In this technology the energy storage is attained in an existing building cooling system which results in a fundamental saving of electrical energy to cool down this building. Therefore the cooling system is used to cool water or ethylene glycol during off-peak hours and to store it into an isolated storage tank. During peak hours the TES system supports the chiller, resulting in a smaller cooling unit which makes it more efficient, if such an approach is planned from the beginning. Baxter [44] states that if a TES system is added later, it amortises itself after 1-3 years. On the other hand if a TES system is considered in the planning phase, it should not have any initial costs because of the smaller size of the cooling system. Apart from that Chen [31] says that it is possible to make a diversification of the different TES systems according to the temperature. Especially in the low temperature area, several universities are doing researches on cryogenic energy storage (CES). In this case, off-peak power is used to generate cryogen (liquid nitrogen or liquid air). In the peak hours the heat from the surrounding environment boils the liquid and the heated cryogen is used to generate electricity through a cryogenic heat engine. But according to Chen this technology is still under development.

3.2.7 Batteries

One of the oldest and well known technologies in energy storage applications is a battery. In this instance, the electrical energy is converted and stored in chemical form. The battery exists out of electrochemical cells that consist of liquid paste or an electrolyte together with an anode (positive electrode) and a cathode (negative electrode). During the discharge progress, a electromechanical reaction between the two electrodes generates a flow of electrons through the external circuit.[31] To charge a battery again it is necessary to apply an external voltage to the electrodes. In general batteries can have a high efficiency and low standby losses. A disadvantage in comparison to other technologies is the relatively short circuit lifetime which is mentioned in the subsections about the different battery types.

Lead acid batteries

First of all, the oldest batteries – the lead acid batteries (LA) which have been invented in 1859 – have to be mentioned. In this design the energy storage capacity and the power rating depend on the size of the electrode. A LA has a duration time of 5 years which indicates a cycle limit of around 250-1000 charge/discharge level.[44]

The reliability of a LA is therefore around 70-90% with a relative low cost range of $300-600/kWh. It has a low energy density of 30-50 Wh/kg. Nevertheless it is still a popular storage choice for power quality, UPS and spinning reserve applications. [31]

Nickel cadmium batteries

The first Nickel cadmium (NiCd) battery was developed 100 years ago. Nowadays three different NiCd designs exists which vary in application areas. The pocket plated NiCd batteries are normally used for standby power, while sintered NiCds are more common in areas where high energy per kg is required, for example starting aircraft and diesel engines. Sealed NiCd are used for commercial products where lightweight, portability and rechargeable power are important. [31]

The advantage of NiCd in comparison to the LA is in a higher energy density 50-75Wh/kg and a high reliability with low maintenance requirements. The cycle life is higher than that of a LA but it is only 2000-2500 times too. In the cost range NiCds can be found with around $1000/kWh[31] which is relatively high. Further NiCd batteries have a memory effect which means that the battery can only be charged fully after full discharge. This has to be taken into account by the battery management procedures.

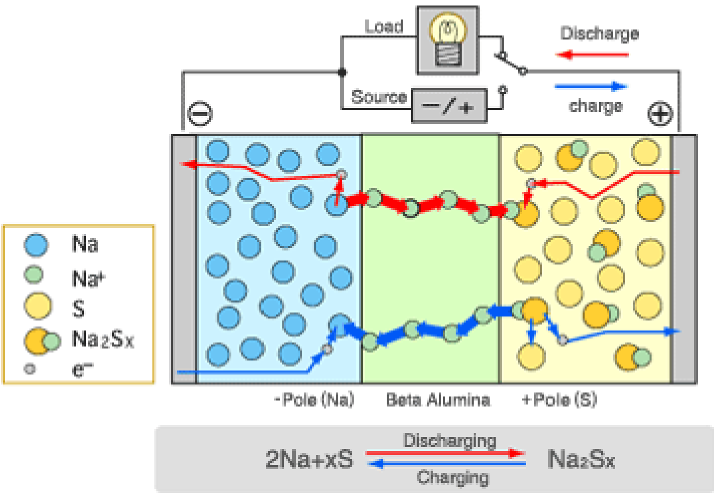
Lithium ion batteries

In this battery the cathode exists out of at lithiated metal oxide ($LiCoO_2$, $LiMO_2$, $LiNiO_2$ etc.) and the anode exists out of graphitic carbon with layering structure. If the battery is charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms.[31]

The first lithium ion battery is only about 20 years old and was developed by Sony. Today's batteries have an energy density of about 200kWh/kg and a life cycle of up to 10000 cycles[31]. Apart from that the efficiency is up to 100%. These facts are the reason why these batteries can be found in about 50% of nowadays small portable devices. Nevertheless the costs being over $600/kWh are a reason why it has not really been successful in the large scale energy market yet.

Sodium sulphur battery

Figure 3-11: Principle of the NAS Battery[46]



A sodium sulphur battery is also known as NaS battery because of the chemical reaction taking place. The battery exists of a positive electrode with liquid (molten) sulphur and a negative electrode with liquid (molten) sodium in it. Both are separated by solid beta alumina ceramic electrolyte that lets only the positive sodium ions go through it and combines with sulphur to form sodium polysulphides ($2Na + 4S \leftrightarrow Na_2S_4$)[47]

The operation temperature for this battery is 300-350C and it has a cycle of life of ~2500 cycles with a total energy range of 150-240Wh/kg. It can have a power pulse capability of 30 seconds which can be six times over its continuous rating. The costs for this storage device is around $350/kWh[31]. A disadvantage is the high operation temperature which requires a heating unit that brings the efficiency to 70-90%.

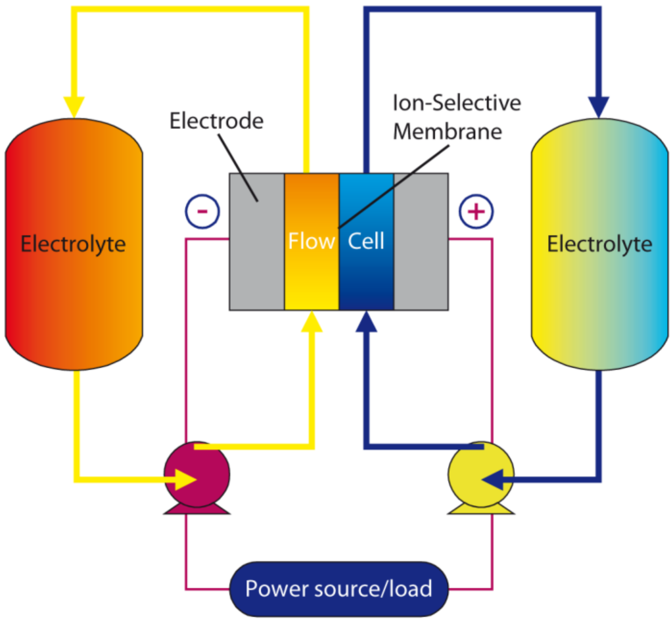
Sodium nickel chloride battery

The sodium nickel chloride battery is also known as ZEBRA battery. Its advantage to a NaS battery is the ability to withstand limited overcharge and discharge. It also has better potential safety characteristics[31]. Nevertheless the energy range is 120Wh/kg, which is lower than that of a NaS battery. Another problem can be that only one manufacturer worldwide produces this battery type and therefore possible customers rely too strongly on a single producer.

3.2.8 Flow batteries

Another approach in comparison to normal batteries is developed in a flow battery. In this type of storage the energy is released through a reversible electrochemical reaction between two electrodes whereas the additional electrolyte is stored externally. See figure below for schematic overview:

Figure 3-12: Schematic overview of a redox flow cell energy storage system[48]

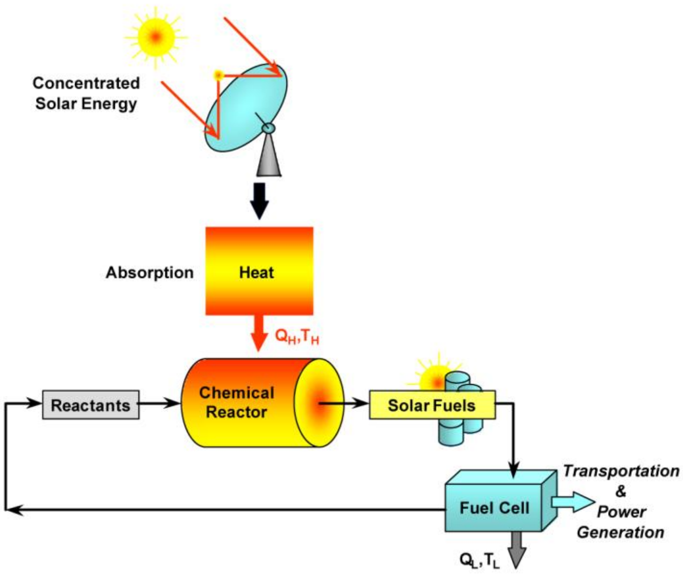


The main difference to a conventional battery is the fact that the energy is stored in the electrolyte solutions. The rating of power and energy is independent from the storage capability. Flow batteries can release energy continuously on a high power for up to 10 hours of discharge. In general there are three different types of flow batteries which are compared in price and technical characteristics in Table 3-1.

3.2.9 Solar fuels

A relatively new technology which is still in development is solar fuel. The general problem of sun-generated energy is normally the storage. If for example solar energy is produced in Australia, this energy cannot be brought to Europe. The solar fuel could solve this problem. If the sunlight is concentrated over a small area with the help of parabolic mirrors and then capture that radioactive energy with the help of suitable receivers, it should be possible to obtain heat at high temperatures for driving a chemical transformation and producing a storable and transportable fuel.[49] The schematic view can be found in Figure 3-13: it describes how concentrated solar radiation is used as the energy source. In this high temperature, the production of storable and transportable fuels is caused by a chemical reaction[49].

Figure 3-13 Schematic of solar energy conversion into solar fuels[49]



3.3 Comparison

3.3.1 Technical

The problem with comparing the previously mentioned technologies is that they have different background situations. For instance, it is important to consider how long a technology has been around and how much knowledge and experience there is in this case. Chen [31] defines three different categories. According to him only PHS and lead-acid batteries are really mature technologies where no big improvements have been made in the last years. Of course there were some developments to improve the efficiencies of turbines and the pumps of the PHS units but in general the main concept of the technologies is still the same. The second group is the developed technologies that include CAES, NiCd, NaS, Zebra, Li-ion, Flow Batteries, SMES, Flywheel supercapacitors and thermal energy storage. These technologies are developed and available but are not as common and too expensive for commercial usage in large scale area. The last group includes technologies as Solar Fuel and CES which are still under development and not available for commercial use. Therefore it is necessary to make more research efforts before these technologies are really reclaimable.

Apart from that some technologies are only made for one application area and others could possibly fulfil requirements of more than one but with different configurations. In general it is common[31, 44, 47] to differ between power quality, bridging power and energy management. In the case of the latter, a high amount of energy is stored and can be released over a long period of time. PHS, CAES and CES are technologies that can be put in this area. Flywheels, SMES and super capacitors deal with power quality usage and have a very small response time and therefore can increase the quality of the power by damping voltage drops. The typical power rating for these technologies is lower than 1MW. The bridging powers fragment is for short response times but also for a long discharge time. Their power rating is normally around 100kW-10MV and includes batteries, flow batteries and fuel cells. The summary of this is given in Table 3-1.

Table 3-1: Technical comparison of different technologies[31]

Systems	Power rating and discharge time		Storage duration	
	Power rating	Discharge time	Self discharge per day	Suitable storage duration
PHS	100-5000 MW	1-24h+	Very small	Hours-months
CAES	5-300 MW	1-24h+	small	Hours-months
Lead-acid	0-20 MW	Seconds-hours	0.1-0.3%	Minutes-days
NiCd	0-40 MW	Seconds-hours	0.2-0.6%	Minutes-days
NaS	50kW – 8 MW	Seconds-hours	~20%	Second-hours
Zebra	0-300 kW	Seconds-hours	~15%	Second-hours
Li-ion	0-100 kW	Minutes-hours	0.1-0.3%	Minutes-days
Solar Fuel	0-10 MW	1-24h+	Almost zero	Hours-months
SMES	100 kW – 100 MW	Miliseconds-8Seconds	10-15%	Minutes-hours
Flywheel	0-250 kW	Milliseconds -15 min	100%	Seconds-minutes
Super-capacitors	0-300kW	Milliseconds -60 min	20-40%	Seconds-hours
CES	100 kW – 300MW	1-8h	0.5-1.0%	Minutes-days
TES	0-60 MW	1-24h+	0.05-1.0%	Minutes-months

The above mentioned characteristics are only commonly used ones. A SMES unit for example can be built with other qualities but that can pose other problems. An example could be the environmental influences with such devices. According to Chen and co-workers[31], the destruction of trees and land for building a reservoir in conjunction with a PHS, the emission from combustions of natural gas with a CAES and the toxic remains of lead-acid batteries have negative influences. Apart from that

SMES units if they should be built for long energy discharge have a strong magnetic field which has possible influences to the environment.

Another issue, previously mentioned, is the different life time of the different technologies and their efficiencies. If a comparison between the different technologies is made, these issues have to be considered in the decision. Therefore a cheap technology with low efficiency can possibly be preferred to a technology that is very expensive but has a low efficiency as well.

Table 3-2 shows an account of the different energy, power density and the life times of the technologies as well as the efficiency.

Table 3-2: Technical comparison of the technologies (sources: [31, 44, 49])

Systems	Life time an cycle life		Energy and power destination		Efficiency
	Life time (years)	Cycle life (cycles)	Wh/kg	W/kg	approximate cycle efficiency in %
PHS	40-60	-	0.5-1.5	-	72-85
CAES	20-40	-	30-60	-	70-85
Lead-acid	5-15	500-1000	30-50	75-300	70-85
NiCd	10-20	2000-2500	50-75	150-300	60-70
NaS	10-15	2500	150-240	150-230	75-90
Zebra	10-14	2500+	100-120	150-200	85-90
Li-ion	5-15	1000-10000+	75-200	150-315	90-99
Solar Fuel[2]	-	-	800-100000	-	20-30
SMES	20+	100000+	0.5-5	500-2000	95+
Flywheel	~15	20000+	10-30	400-1500	80-95
Super-capacitors	~5	50000+	0.05-5	~100000	80-95
CES	20-40		150-250	10-30	40-50
TES[5]	5-15		80-200	-	See note

Note: data collected from the different sources and formatted in this table
Note 2: relative low efficiency because only a small amount of the sun is converted (~ 18%)

The table shows again that a simple comparison is not really possible because all the different needs and wishes have to be considered. The different technologies have benefits in different areas and this has to be considered when the storage application is planned. Nowadays, the biggest arguments for or against any technology revolve around the costs. Therefore the next section provides an indication to compare the technologies on the price area.

3.3.2 Costs

After the application aspect for a storage device is determined, the last factor to consider when deciding for or against the acquirement of such a technologies is always the price. If the direct savings through the usage of a storage technology is higher than its operation and its investment costs, the decision is mostly easy. An example could be shifting the load from a peak to an off peak period[50] which results in a direct saving of energy and money. But these cases are very rare. Normally the indirect savings are more common. In that case an installation of a storage technology can result in a reduction of possible down times or in an improvement of the quality of energy – to suit the requirements of the customer – which then again saves money.

To have an overview of the different costs of the different technologies Table 3-3 [31, 44] combines costs per kW, costs per kWh and costs per kWh per cycle.

Table 3-3: Costs of the different technolgies (main source: [31] + different others ([44, 49, 51]))

Systems	costs		
	Euro/kW	Euro/kWh	Euro/kWh-per cycles
PHS	600-2000	5-100	0.1-1.4
CAES	400-800	2-50	2-4
Lead-acid	300-600	200-400	20-100
NiCd	500-1500	800-1500	20-100
NaS[2]	1000-3000	300-500	8-20
Zebra	150-300	100-200	5-10
Li-ion	1200-4000	600-2500	15-100
Solar Fuel[3]	-	~2000	-
SMES	200-300	1000-10000	-
Flywheel	250-350	1000-5000	3-25
Super-capacitors	100-300	300-2000	2-20
CES	200-300	3-30	2-4
TES[5]	200-400	30-60	-

Note: to convert currency to Euro, the average exchange rate of the years in which the source is published has been taken.
Note 2: [44] gives ~650Euro/kW in 2006
Note 3: [49] speak 2002 about 2000Euro per kWh
Note 4: [44] indicates 200-400 Euro/kW in 2006

The three different cost issues show again that it is very difficult to make a definite statement on the better technology. First of all, the issue used to compare different technologies has to be determined. The Euro/kWh- per cycle category is therefore defined as cost per unit energy divided by the cycle life (Table 3-2). This value is good for a comparison in a frequent storage/discharge application (for example load levelling) because the claim on a high life cycle is taken into account[31]. The Euro/kW metric is in contrast to that a good guide for upfront costs. The Euro per kWh is useful to have an idea of operation costs.[44]

One example shows that a PHS has very low kWh prices per cycles and is therefore very useful for load levelling. On the other hand, it has a high amount of initialisation costs for the reservoirs. It was not possible to find prices for solar fuels because that this technology is still at the beginning of its development and is not available for everyday usage. This is a general problem with developing technologies because the research facilities have normally less interest in the economical data of such a project.

They want to get information on the technological possibilities, regardless of whether this technology is going to be used in daily routines or not. An example is Dr. Michael Steurer (Florida State University, Leader Power Systems Research Groups) who tries “to stay clear of the commercial/economical aspect since anything you extract is a guess at best”.[52]

3.4 Summary

Different technologies are made for different application areas and therefore difficult to compare. For that reason it has to be clear when a storage technology should be used. For energy management applications PHS, CAES, large/scale batteries, flow batteries, fuel cells, solar fuels, TES and CES are useful. Flywheels, SMES, batteries, super capacitors are more appropriate for power quality and short duration UPS. Batteries, fuel cells could be used for bridging power application. If this is clear, the different available technologies that are eligible can be researched further for technology and economical differences. Another thing to consider is whether the use of the technology could possibly deliver new information or if a matured technology is more useful for the application area because planning is more possible. Normally, industry companies prefer to use mature technologies because of fewer ‘surprises’ in the usage. If a new technology is used, it can have impacts on the down times and therefore on the total efficiency of a system which can result in a miscalculation of the whole project. Another point is that a technology that is susceptible for failures or at least not reliable has to be better monitored to avoid or minimise possible interruptions. Therefore this type of technology will possibly only be used in test applications or at least not in combination with high critical applications. A SMES system as an example is from the theory a developed technology but worldwide there are no large scale SMES Units in operation. This results in high initialisation costs, influences of the magnetic field and possibly other troubles in combination with this technology. The first concern and aim of an industry is to earn money and they have to be able to plan it. If a new technology is used for the first time, it cannot be assured that this aim is achieved. Because some of the technical and economical data from the newer technologies mentioned in this paper are obtained only from research facilities and not real-life situations, they have to be critically considered if connections to real applications are ever to be made.

But in general it is expected that the inset of storage technologies will increase in the next years because of the expanding use of renewable energies around the world. For these technologies it is often fundamental to store the produced energy and release it later.

4. CONCLUSIONS AND FUTURE WORK

4.1 Conclusion

The power system utilities have high potential to save money and to increase the efficiency of systems. If the transformer maintenance is improved, not only the lifetime is extended but it is also possible to save money. Besides that, the reliability is extended and possible failure can be recognised before they occur. This results in a better overview of the whole system which is nowadays important for the operators.

In the energy storage area, it is not possible to find the “best” technology. It has to be determined in which application area the storage device is necessary. With this information the rating of the different technologies need to be done. It has to be taken into account that some of the technologies are still in development or are at least at the beginning of their economical usage. Therefore the reliability is not always guaranteed. Nevertheless it is expected that the next years will bring knowledge in the energy storage area because of the increasing usage of renewable energies which depend on the cyclic occurrence of the sun, wind or others. Therefore it is only possible to enlarge the usage if the energy is stored in some way.

4.2 Future Work

The problem with cost studies is mostly due in the information collection of the economical data. This became clear during this project. Therefore it could be a good idea to make research on transformer maintenance under the economical aspect together with an industrial partner who uses transformers in its own facilities. Information about the technical issues on transformer maintenance is available in databases and books but the economical side is often not published and made available to the public.

The same problem occurs with the energy storage area; in this field the economical information is hard to assess. Therefore an economical research could be made with a partner who produces storage devices and can appoint at least a specific price for a precise product.

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Appendix A

Actions based on TDCG (**Source IEEE Std C57.104-2008 [23])**

	TDCG levels (μL/L)	TDCG rate (μL/L/day)	Sampling intervals and operating procedures for gas generation rates	
			Sampling interval	Operating procedures
Condition 4	>4630	>30	Daily	Consider removal from service. Advise manufacturer.
		10 to 30	Daily	
		<10	Weekly	Exercise extreme caution. Analyse for individual gases. Plan outage. Advise manufacturer.
Condition 3	1921 to 4630	>30	Weekly	Exercise extreme caution. Analyse for individual gases. Plan outage. Advise manufacturer.
		10 to 30	Weekly	
		<10	Monthly	
Condition 2	721 to 1920	>30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
		10 to 30	Monthly	
		<10	Quarterly	
Condition 1	≤720	>30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
		10 to 30	Quarterly	Continue normal operation.
		<10	Annual	

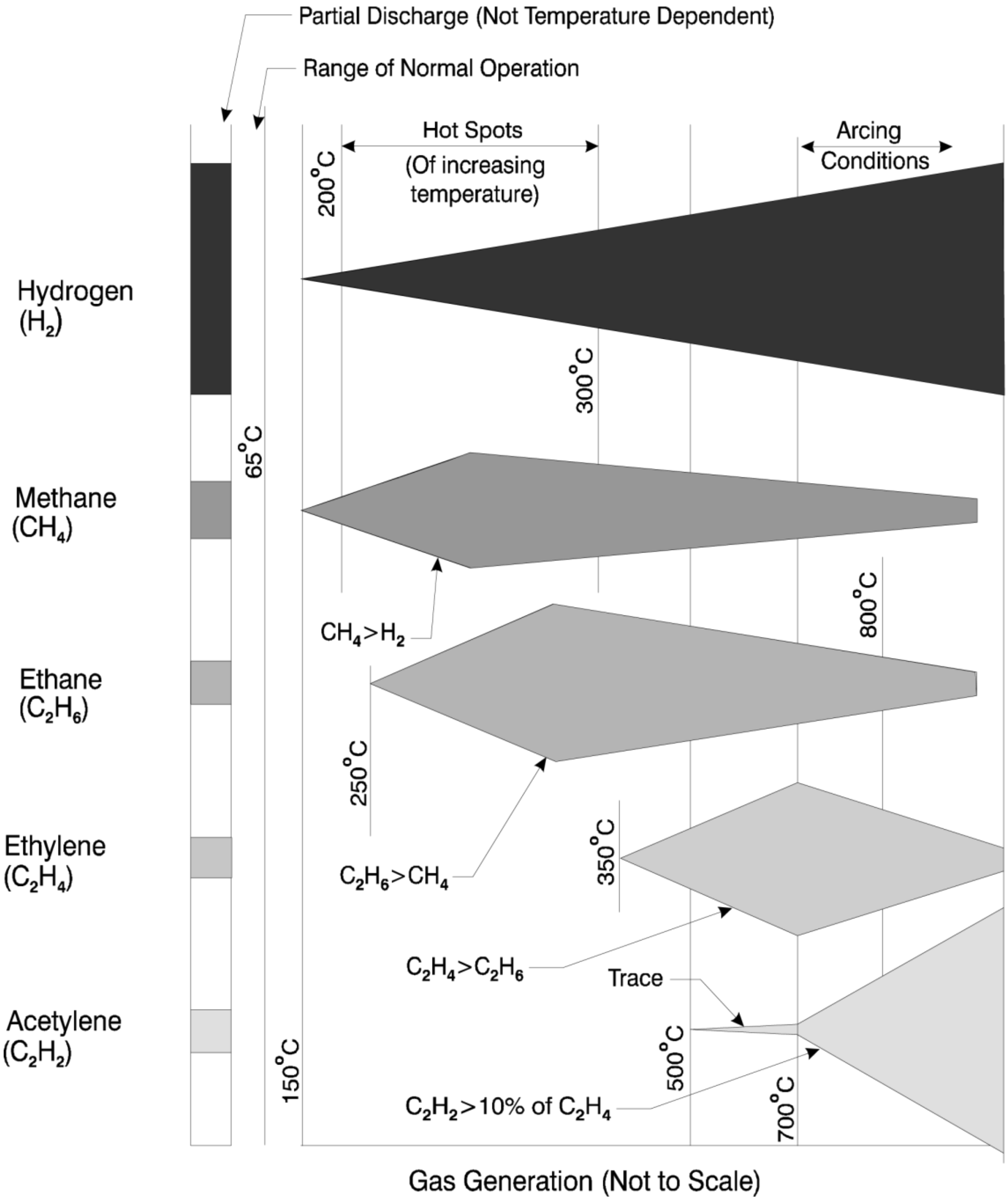
Appendix B

Dissolved Gas Analysis Detection Limits. (**Source Transformer Maintenance[24])**

Hydrogen (H_2) about 5 ppm
Methane (CH_4) about 1 ppm
Acetylene (C_2H_2) about 1 to 2 ppm
Ethylene (C_2H_4) about 1 ppm
Ethane (C_2H_6) about 1 ppm
Carbon monoxide (CO) and carbon cioxide (CO_2) about 25 ppm
Oxygen (O_2) and nitrogen (N_2) about 50 ppm

APPENDIX C

Combustible Gas Generation vs. Approximate Oil Decomposition Temperature (**Source: Transformer Maintenance[24])**



Approximate Oil Decomposition Temperature above 150°C

APPENDIX D

Rogers Ratios for Key Gases (**Source: Transformer Maintenance[24]**)

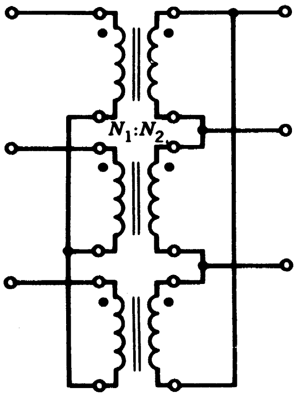
Code range of ratios		$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{C_2H_4}$	Detection limits and 10 x detection limits are shown below:
<0.1		0	1	0	C_2H_2 1 ppm 10 ppm
0.1-1		1	0	0	C_2H_4 1 ppm 10 ppm
1-3		1	2	1	CH_4 1 ppm 10 ppm
>3		2	2	2	H_2 5 ppm 50 ppm
					C_2H_6 1 ppm 10 ppm
Case	Fault Type				Problems Found
0	No fault	0	0	0	Normal aging
1	Low energy partial discharge	1	1	0	Electric discharges in bubbles, caused by insulation voids or super gas saturation in oil or cavitation (from pumps) or high moisture in oil (water vapor bubbles).
2	High energy Partial discharge	1	1	0	Same as above but leading to tracking or perforation of solid cellulose insulation by sparking, or arcing; this generally produces CO and CO_2
3	High energy discharges, sparking, arcing	1-2	0	1-2	Continuous sparking in oil between bad connections of different potential or to floating potential (poorly grounded shield etc); breakdown of oil dielectric between solid insulation materials.
4	High energy Discharges, arching	1	0	2	Discharges (arcing) with power follow through; arcing breakdown of oil between windings or coils, or between coils and ground, or load tap changer arcing across the contacts during switching with the oil leaking into the main tank
5	Thermal faults less then 150°C (see note 2)	0	0	1	Insulated conductor overheating; this generally produces CO and CO_2 because this type of fault generally involves cellulose insulation.
6	Thermal fault temp. rang 150-300°C (see note 3)	0	2	0	Spot overheating in the core due to flux concentrations. Items below are in order of increasing temperatures of hot spots. Small hot spots in core. Shorted laminations in core. Overheating of copper conductor from eddy currents. Bad connection on winding to incoming lead, or bad contract on load or no-load tap changer. Circulation currents in core; this could be an extra core ground, (circulating currents in the tank an core); this could also mean stray flux in the tank. These problems may involve cellulose insulation which will produce CO and CO_2
7	Temp fault temp. range 300-700°C	0	2	1	
8	Temp fault temp range over 700°C (see note 4)	0	2	2	

Notes:

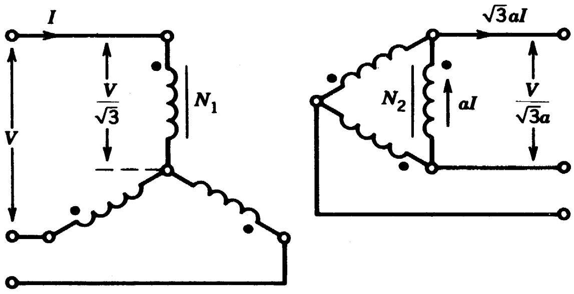
1. There will be a tendency for ratio C_2H_2/C_2H_4 to rise from 0.1 to above 3 and the ratio C_2H_4/C_2H_6 to rise from 1-3 to above 3 as the spark increases in intensity. The code at the beginning stage will then be 1 0 1.
2. These gases come mainly from the decomposition of the cellulose which explains the zeros in this code.
3. This fault condition is normally indicated by increasing gas concentrations. CH_4/H_2 is normally about 1, the actual value above or below 1, is dependent on many factors such as the oil preservation system (conservator, N_2 blanket, etc.), the oil temperature, and oil quality.
4. Increasing values of C_2H_2 (more than trace amounts), generally indicates a hot spot higher than 700 °C. This generally indicates arcing in the transformer. If acetylene is increasing and especially if the generation rate is increasing, the transformer should be de-energized, further operation is extremely hazardous.

APPENDIX E

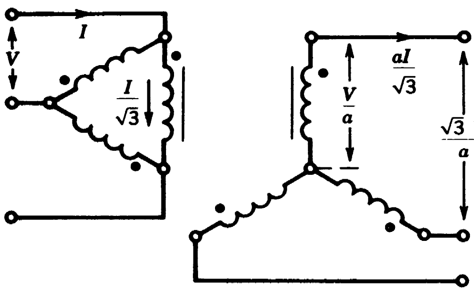
Three-phase transformer connections (**Source: Principles of Electric Machines and Power Electronics [6])**



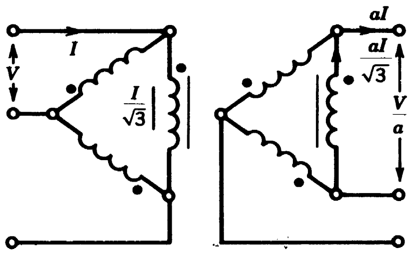
(a) Y - Δ



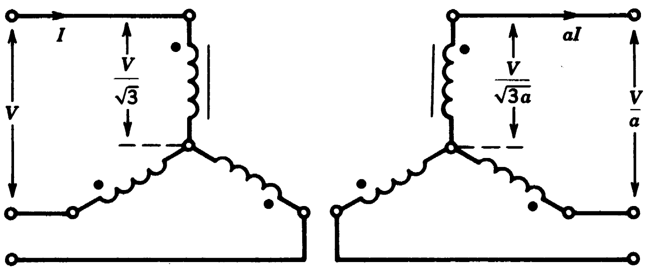
(b) Y – Δ



(c) Δ - Y



(d) Δ – Δ



(e) Y - Y

Final assessment

Administrative data

Given – Surname student:	Sebastian Broecker
Student number HsZuyd / Curtin:	0735655 / 14257285
Phone student:	+61413806822
University/Company:	Curtin University of Technology
Phone supervisor Curtin:	+61892667287
Name Supervisor HsZuyd:	Ing. Leon M.C. Muijtjens
Name Supervisor Curtin University of Technology:	Dr. Ahmed Abu-Siada
Period:	Feb.2009 – Jun 2009
Project Title: Cost study for Power System Utilities	

Information Supervisor Curtin University of Technology:

We ask you to fill in the table on the next page and to find improvements in consultation with the student afterwards.

Evaluation

Competence	mark (1 t/m 10)	weight	mark x weight
Understanding Quality of the problem analyse	9	1	9
Design Quality conceived solutions	8	1	8
Planning and perfomance Quality planning and execution	10	1	10
Occupation Specific skills Quality knowledge, skill and professional attitude	9	1	9
General competencies • independence • planned working • oral communication • cooperate in a team • social skills • self reflection	9	2	18
mark (weighted sum divided by 6):			9

Improvements:

- Mr. sebastian has shown excellent research skills during his study. He has a very good communication skill. that has been reflected on his presentation.
- Mr. sebastian was under exchange program & he had to submit his thesis within one semester only and from my point of view he could deliver a good and as much work as those who doing their project in two semesters.
- He has obtained 11 out of 15 in his presentaion & 75% in his thesis. The only comment from the examiners was about the theoritical point he has investigated in his research. However, this research meant to be more into bussiness than technical work.

Report (Curtin University)

Formal completeness

The report contains a:

- ❑ summary
- ❑ title page
- ❑ cover
- ❑ preface
- ❑ table of contents
- ❑ the sections flow in systematic manner
- ❑ Introduction
- ❑ chapter introduction
- ❑ illustrations (table, charts)
- ❑ reference list
- ❑ appendix
- ❑ source listings where necessary

Language and structure

Readable style, correct spelling and punctuation ....9... (10)
Logical flow of ideas .....8...(10)
Typography ....9....(10)
subtotal (max.30) ....26.......

Content

Clarity and definition of the problem statement ..17....(20)
Description and justification of the chosen solution .20...(30)
description of the development .12....(20)

subtotal (max 70) 49............
total score (max 100) ..75.........

Cijfer verslag (totaalscore/10): 7.5

Presentation *(HSZuyd)*

	Cijfer (1 t/m 10)
Inleiding *Omgevingsbeschrijving* *Maakt centrale vraag duidelijk* *Geeft doelstelling aan*	
Kern: *Presentatie is samenhangend* *Maakt eigen werk duidelijk* *Goede diepgang* *Infowaarde voor publiek*	
Slot *Goede presentatie van de conclusies* *Goede uitleiding* *Goede omgang met vragen*	
Spreektechniek *Goed stemvolume* *Goed spreektempo* *Duidelijke articulatie*	
Houding *Functionele gebaren* *Open houding naar publiek*	

Cijfer voor de presentatie:

Eindcijfer onder voorbehoud van goedkeuring door de eindexamencommissie

Via onderstaande tabel wordt het eindcijfer vastgesteld. De volgende opmerkingen zijn van belang:

- Mocht u redenen hebben om een cijfer 9 of hoger te adviseren dan horen wij deze graag. Als de docentbegeleider uw advies ondersteunt wordt een andere docentbegeleider verzocht ook zijn mening te geven over deze beoordeling. Is deze ook dezelfde mening toegedaan dan wordt het betreffende cijfer toegekend.
- Mocht u redenen hebben om een cijferlager dan 6 te adviseren dan horen wij dit minder graag ☺. Als de docentbegeleider uw advies ondersteunt wordt een andere docentbegeleider verzocht ook zijn mening te geven over deze beoordeling. Is deze ook dezelfde mening toegedaan dan wordt het betreffende cijfer toegekend.

N.B! Een onvoldoende voor de afstudeeropdracht betekent dat het diploma niet behaald kan worden.

		Opmerkingen
80 % van het cijfer voor de uitvoering:	9	Cijfer uitvoering lager dan 6 -> eindcijfer onvoldoende
10% van het cijfer voor het verslag	7.5	Definitief verslag onvoldoende -> eindcijfer onvoldoende
10% van het cijfer voor de eindpresentatie		
Eindcijfer		

Handtekening bedrijfsbegeleider: A. Siadu

Handtekening student: S. Broch

Handtekening docentbegeleider:

Datum: 19.06.09