KURZFASSUNG

Der Verlauf der Kurzschlussspannung über einen Regelbereich wird maßgeblich von der Wicklungsanordnung bestimmt. Im Zuge dieser Diplomarbeit wird diese für Spartransformatoren für ausgewählte Regelungsarten, Regelungsschaltungen und Wicklungsanordnung über den Regelbereich berechnet und grafisch dargestellt.

Diese Diplomarbeit soll zum einen einen Überblick über den aktuellen technologischen Stand der Aktivteil - Auslegung liefern. Da die Aktivteil - Auslegung in der Angebotsphase die meiste Zeit in Anspruch nimmt, soll durch die Kombination, aus der geforderten Kurzschlussspannung und den Kurzschlussspannungsverläufen die Möglichkeit einer Vorauswahl der Wicklungsanordnung gegeben werden. Durch diese Vorauswahl bekommt der Entwickler mehr Zeit für die Optimierung der weiteren Teile des Aktivteils. Zum anderen sollen die Kurzschlussspannungsverläufe rechnerisch ermittelt und anschließend grafisch dargestellt werden um für die Vorauswahl verwendet werden zu können.

Schlüsselwörter:

Kurzschlussspannung – Regelungsschaltung – Wicklungsanordnung- Regelungsarten - Aktivteil

ABSTRACT

The trend of the short circuit impedance over a regulation range depends on the winding arrangement. In this Master thesis the short circuit impedance for autotransformers over a regulation range is calculated and presented for different voltage regulation types, regulation types and winding arrangements.

The thesis gives an overview of the actual technologies for the active part design. At the very beginning, the electrical designer needs most of the time for the active part design but with the combination of the given short circuit impedance limits and the trends of them, it is possible to make a preselection of winding arrangements which full fill the short circuit impedance limits and the whole tendering phase. With this preselection there is more time available for the optimisation processes of the other components of the active part. Therefore the short circuit impedance values along the regulation range will be calculated and graphical presented to be available for the preselection.

Key words:

Short circuit impedance – Regulation types – Voltage regulation types - Winding arrangements - Active part

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1. Introduction

1.1 Main Task

The short circuit voltage is one of the main parameters for transformer designer. To use transformers in parallel operation it is important that the rated short circuit voltage varies only in a range of 10% to avoid that the transformer with the lower u_k will be overloaded. It is also necessary to know the short circuit voltage to calculate the maximum possible short circuit current for the secondary side in case of a short circuit. Therefore all components must be designed to withstand this short circuit current.

The Motivation for the Master Thesis is to show the dependence of the short circuit voltage on the winding arrangement, the voltages on primary and secondary and the chosen regulation type. It helps the electrical designer to make a preselection of possible transformer winding arrangements to meet customer requirements. To give them more designing time for the active part to full fill the specified losses. Further to show which parameters affect the short circuit voltage and to compare the results of an autotransformer with them of a transformer. At the moment there exist some charts which show the dependence of the short circuit voltage from supply voltage and the position of the windings. One is published in “Methods and Means of Voltage Regulation of large Autotransformers”[1] but the resolution of the regulation range of the voltages and the number of the calculated values for the short circuit impedance is insufficient for the daily work because values are only calculated for the nominal, minimum and maximum tap position but not for positions in between them. In the thesis the short circuit voltage calculation is done more detailed, for a wider regulation range and with the different types of regulation. At the beginning of the thesis there will be an introduction to the basic principles of transformers to give an overview how a transformer works. Then we take a look to the different components of the active part of a transformer and especially how they affect the operation of the transformer and to give an overview about the state of the art of designing the active part and to show the factors by which the electrical designer is limited during the tendering phase. After this basic overview we take a look how we can calculate the impedance and we will calculate them for different transformer configurations.

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[1] B. Heller, "Methods and means of voltage regulation of large auto transformers
," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2011 8th International Conference On,* 1973, pp. 9-24

1.2 Definition of a MPT and LPT

The short circuit impedance should be calculated for medium power transformers (MPT) and large power transformers (LPT). The following figure shows the definition from the company, in case of the voltage and the rated power for this transformer types.

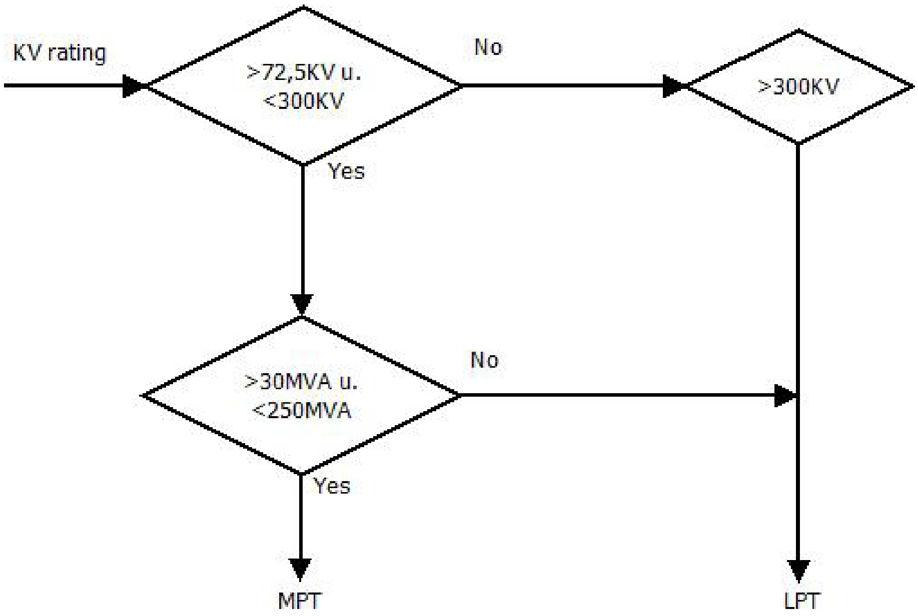

FIGURE 1.2-1 DEFINITION OF A MPT AND LPT[2]

1.3 Definition of the short circuit voltage/impedance

The short circuit voltage in percent or sometimes short circuit impedance is the necessary voltage on the primary side, to reach the rated current on the secondary, in the case of a short circuited secondary. There are two types of transformers for a low short circuit voltage the transformer is “stiff voltage” this means that under an increasing load the voltage drop is very low and secondary voltage remains more or less constant. A low short circuit voltage results in a high short circuit current which could be a problem for devices and substations in the power grid. A transformer with a higher short circuit voltage is “soft voltage” which means that under an increasing load the voltage drop is high and the secondary voltage sinks. With a higher short circuit voltage you get the advantage of a lower short circuit current. In the following table are some recommended values for the short circuit impedance in dependence on the rated power for a three phase two winding transformer.

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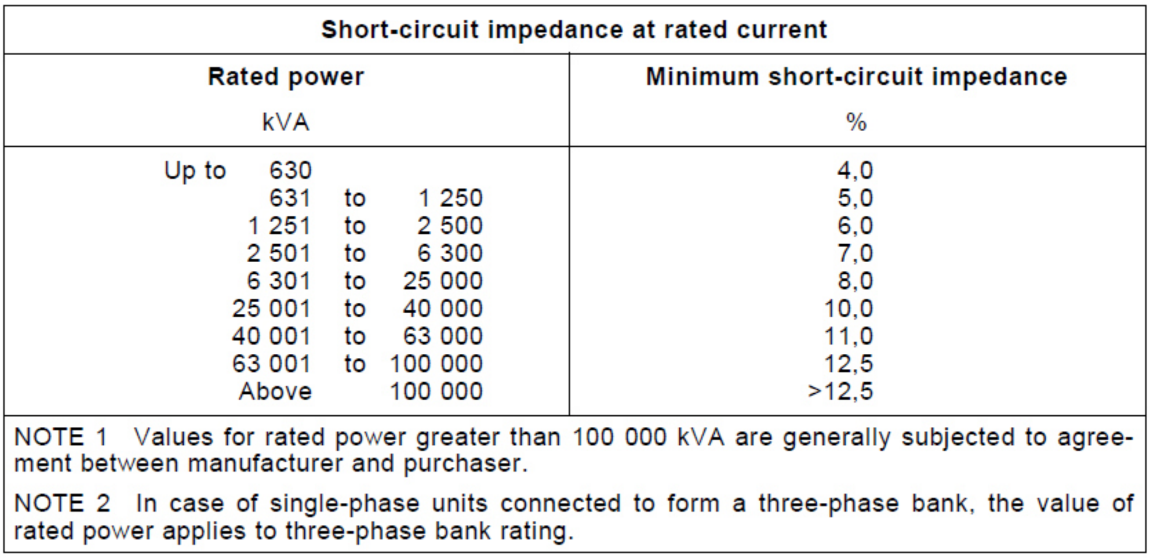
[2] Company A, Definition of a MPT and LPT



Short-circuit impedance at rated current	
Rated power kVA	**Minimum short-circuit impedance** %
Up to 630	4,0
631 to 1 250	5,0
1 251 to 2 500	6,0
2 501 to 6 300	7,0
6 301 to 25 000	8,0
25 001 to 40 000	10,0
40 001 to 63 000	11,0
63 001 to 100 000	12,5
Above 100 000	>12,5

NOTE 1 Values for rated power greater than 100 000 kVA are generally subjected to agreement between manufacturer and purchaser.

NOTE 2 In case of single-phase units connected to form a three-phase bank, the value of rated power applies to three-phase bank rating.

TABLE 1 - MINIMUM VALUES OF SHORT CIRCUIT IMPEDANCE AT RATED POWER FOR TRANSFORMERS WITH TWO SEPERATE WINDINGS (IEC60076 PART 5)[3]

2. Transformer

The following chapter should give an overview of the principle operating of the two most common types of a transformer. It starts with the basic equations and includes the transformer losses, conductors and windings to the core material and ends at the insulation of the machine.

2.1 Transformer and Autotransformer

In principle there are two main transformer types. One is the separated winding transformer, which we will call only “transformer” in this thesis and the other one is the “autotransformer”. With these two types you can describe the principles of all transformers. The main difference is that the “transformer” has two galvanic separated windings one for the primary and one for the secondary. They both are not electrical connected to each other. The energy transfer from primary to secondary is based on electromagnetic induction. Instead of a transformer, in an autotransformer the windings are not galvanic separated and they connected in that way that it looked like one winding, where parts are used for both the primary and the secondary side. A part of the energy transfer is based on the electromagnetic induction and the other part is electrically transferred via conductors from one side to the other.

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[3] "Power Transformer Part 5: Ability to withstand short circuit," *IEC 60076-5:2000 Edition 2. 0 2000-07,* 2000.

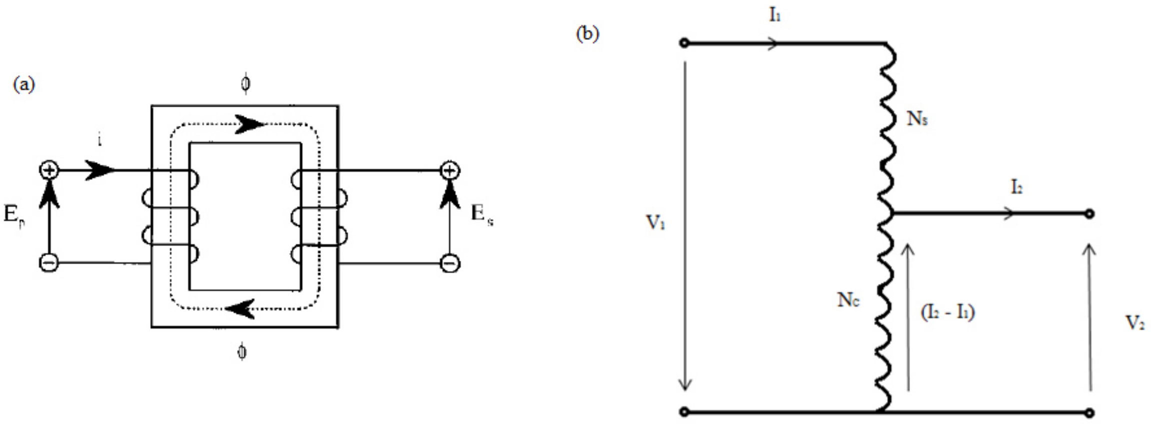

FIGURE 2.1-1 (A) SEPARATE TWO WINDING TRANSFORMER[4] (B) AUTOTRANSFORMER

2.1.1 Transformer

A transformer is an electrical machine with no moving parts which links two electrical grids, where both operate with the same frequency but have different voltages to allow electrical energy transfer from one grid to another one. With no electrical connection between the two grids, the connection is made electromagnetically. The explanation of the main principles of a transformer is shown with a single phase transformer and with an ideal transformer. This means that the whole flux flows in the core and there is no leakage flux and we neglect all losses at the beginning. When the secondary side is open and the primary is supplied with a sinusoidal voltage, this means we have no load condition there is only a small primary side current I_0 the magnetizing current needed to create the magnetic flux in the core. With Faraday`s law we get for the *emf* e_1 of the primary side:[5]

$$e_1 = -N_1 \cdot \frac{d\varphi}{dt}$$

Because of the sinusoidal supply voltage the created magnetic flux is also sinusoidal, therefore we get.

$$e_1 = N_1 \cdot \omega \cdot \varphi_{mp} \cdot \cos \omega t$$

For the RMS of *emf* e_1 which is the so called “transformer universal EMF equation” we get:

$$E_1 = 4.44 \cdot \varphi_{mp} \cdot f \cdot N_1$$

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[4] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter1 page 32

[5] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 1 Page 11-12

For the *emf* e_2 of the secondary side we get:

$$e_2 = -N_2 \cdot \frac{d\varphi}{dt}$$

For the RMS of *emf* e_2 we get:

$$E_2 = 4.44 \cdot \varphi_{mp} \cdot f \cdot N_2$$

So you get that the ratio between E_1 and E_2 depends on the winding turns of the primary and the secondary side

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

If a load is connected with the secondary side of the transformer a current will flow in the secondary side. Due to **Lenz Law** the current will oppose the change of the magnetic flux φ and tries to reduce them. In an ideal transformer the main voltage should remain constant therefore the flux must remain constant and to hold the flux constant the primary current must be increased. The new primary current I_1 is now the vector sum of I_0 and the load current I_1' which is needed to neutralize the demagnetizing effect of the secondary side. However for an ideal transformer with infinite permeability magnetic material we can neglect I_0 therefore the primary current is only the load current. Therefore we can see that the primary side ampere turns are equalize the secondary side ampere turns. [6]

$$I_1 \cdot N_1 = I_2 \cdot N_2$$

As the name "ideal transformer" says it is only an ideal construction, in real life such a transformer doesn't exist. A real transformer has resistivity of conductor and because of the alternating magnetic field there are two types of losses in the magnetic material, eddy current losses and hysteresis losses. We will discuss them later. In a real transformer are also some parts of the flux are not linked with the core. That so called leakage flux produces a voltage drop on the primary and on the secondary side of the transformer. So we get the equivalent circuit for a real transformer:[7]

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[6] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 1 Page 12-15

[7] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 1 Page 15-17

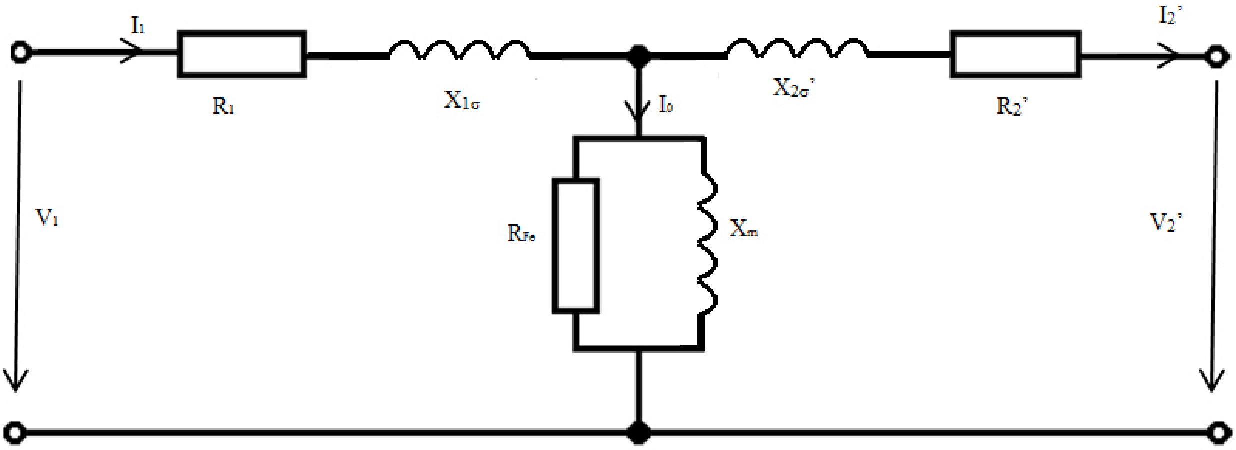

FIGURE 2.1.1-1 EQUIVALENT CIRCUIT OF A SINGLE PHASE REAL TRANSFORMER

Transformer parameters:

R_1 … primary side resistance
$X_{1\sigma}$ … primary side leakage reactance
R_2' … secondary side resistance referred to primary side
$X_{2\sigma}$' … secondary side leakage reactance referred to primary side
X_m … magnetizing reactance
R_{Fe} … resistance representing core losses
V_1 … primary side Voltage
V_2' … secondary side Voltage referred to primary side
I_1 … primary side Current
I_2' … secondary side Current referred to primary side
I_0 … no load current

2.1.2 Autotransformer

Compared to a transformer, an autotransformer has only one winding. This is used for both the primary and the secondary side. This type of transformer can be used when there is no galvanic insulation between primary and secondary side necessary but this could also be a disadvantage of this typ. Main advantages of them are reduced size, weight and costs compared to a two winding transformer with the same electrical specifications. The reason is the power is not only transferred via induction from the primary to the secondary it is also transferred via conduction. The transformer laws explained in 2.1.1 are still valid.[8]

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[8] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 4 Page 129-130

“1. The volts per turn in the common winding equal the volts per turn in the series winding. The common winding voltage divided by the series winding voltage is equal to the number of turns in the common winding divided by the number of turns in the series winding.

2. The sum of ampere-turns of the common winding plus the ampere-turns of the series winding equal the magnetizing ampere-turns. The magnetizing ampere-turns are practically zero, so the magnitude of the ampere-turns in the common winding is approximately equal to magnitude of ampere-turns in the series winding. The series winding current divided by the common winding current is equal to the number of turns in the common winding divided by the number of turns in the series winding.

3. The KVA transformed in the series winding equals the KVA transformed in the common winding.”[9]

Let’s describe the function of them on a star-star connected 400/220KV 400MVA Autotransformer (for example YN0d5 where the “0” shows that it is an autotransformer):

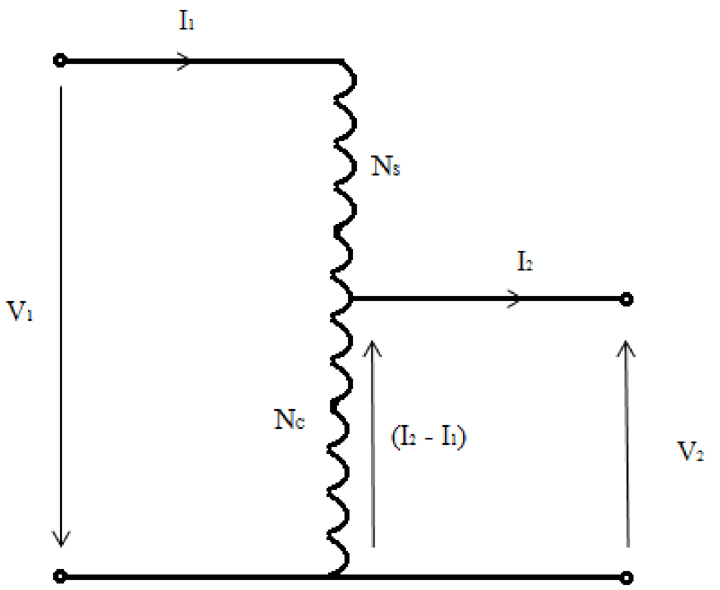

FIGURE 2.1.2-1 AUTOTRANSFORMER

Autotransformer parameters:

I_1 … Input current
I_2 … Output current
V_1 … Input voltage over series and common winding
V_2 … Output voltage over common winding
N_S … Series winding
N_C … Common winding

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[9] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 4 Page 131

The input current I_1 will be

$$I_1 = \frac{S}{\sqrt{3} \cdot V_1} = \frac{400MVA}{\sqrt{3} \cdot 400KV} = 577.4A$$

The output current I_2 will be

$$I_2 = \frac{S}{\sqrt{3} \cdot V_2} = \frac{400MVA}{\sqrt{3} \cdot 220KV} = 1050A$$

Therefore we can calculate the current over N_C , let's call them I_C

$$I_C = I_2 - I_1 = 1050A - 577.4A = 472.6A$$

The $KVA_{through}$ of the autotransformer is S which is 400MVA this is the power which is transferred by conduction and induction from the input to the output. For a normal transformer all the power would be transferred by induction but when we now take a look to the $KVA_{transfer}$ of the autotransformer, which is due to the transformer laws mentioned above KVA_{common} equals KVA_{series} and we calculate it

$$KVA_{common} = KVA_{series} \rightarrow I_C \cdot V_2 \cdot \sqrt{3} = I_1 \cdot (V_1 - V_2) \cdot \sqrt{3}$$

$$472.6A \cdot 220KV \cdot \sqrt{3} = 577.4A \cdot (400KV - 220KV) \cdot \sqrt{3} = 180MVA$$

We see that $KVA_{transfer}$ doesn't equal $KVA_{through}$, the ratio between them is called capacity multiplication factor F_C. This capacity multiplication effect comes from the fact that the power is not only transferred via induction but also with conduction because the common winding is part of both, input and output.

For this example we get for F_C

$$F_C = \frac{KVA_{through}}{KVA_{transfer}} = \frac{400MVA}{180MVA} = 2.22$$

This factor is a function of the voltage ratio r between input and output

$$r = \frac{V_1}{V_2} = \frac{400KV}{220KV} = 1.818$$

$$F_C = \frac{r}{r-1} = \frac{1.818}{1.818 - 1} = 2.22$$

F_C becomes very large for $r \approx 1$ which means that most of the power is transferred via conduction. Therefore most of the winding is used for both sides, these results in a reduction of costs and volume because less copper is needed. Otherwise when r increases, F_C decreases and the benefits of an autotransformer compared to a transformer decreases.[10]

Generally "the impedance of a transformer can be determined by measuring the impedance across the primary terminals with the secondary terminals short circuited"[11] The short circuit impedance of an autotransformer compared to them of a two winding transformer with 400KV/220KV with an output power which equals the $KVA_{transfer}$ is

$$\frac{uk_{AT}}{uk_{TR}} = (\frac{V_1 - V_2}{V_1})^2$$

Where uk_{AT} is the short circuit impedance of the autotransformer and uk_{TR} is from the two winding transformer. When we also take into account that the output power of the autotransformer with the same voltage levels is higher and it is the new KVA_{base} the full ratio between the short circuit impedances will be

$$\frac{uk_{AT}}{uk_{TR}} = (\frac{V_1 - V_2}{V_1})^2 \cdot (\frac{S_{AT}}{S_{TR}})$$

This can be simplified to:

$$\frac{uk_{AT}}{uk_{TR}} = \frac{1}{F_C}$$

This ratio will be needed later for the calculations. Therefore it is clear that an autotransformer will have lower losses but higher short circuit currents.

2.2 Losses

"Transformer losses are broadly classified as no-load and load losses. *No-load Losses* occur when the transformer is energized with its rated voltage at one Set of terminals, but the other sets of terminals are open circuited so that no through current or load current flows. In this case, full flux is present in the core, and only the necessary exciting current flows in the windings. The losses are predominately core losses due to hysteresis and eddy currents produced by the time-varying flux in the core steel. *Load losses* occur when the output is connected to a load so that current flows through the transformer from input to output

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[10] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 4 Page 132-134

[11] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 4 Page 134

terminals. Although core losses also occur in this case, they are not, by definition, considered part of the load losses."[12]

For the customers it is important to know the guaranteed losses of the transformer according to their technical specification. Losses are power that cannot be delivered to end customers and cause substantial costs. A criteria for transformer offers of different manufacturers are the capitalized costs by loss evaluation this is called Cost for Ownership and consists of:

$$Cost\ of\ Ownership = capital\ cost + cost\ of\ no\ load\ loss + cost\ of\ load\ losses$$

$$cost\ of\ no\ load\ loss = no\ load\ loss\ [kW] \cdot capitalization\ factor\ \left[\frac{€}{kW}\right]$$

$$cost\ of\ load\ loss = load\ loss[kW] \cdot capitalization\ factor\ \left[\frac{€}{kW}\right]$$

2.2.1 No load losses

As mentioned above no load losses are more or less core losses produced by the hysteresis and eddy currents. Losses due to the no-load current in the winding exist but these losses are so small that they can be neglected without any problem. They result from the magnetizing current and the alternating flux in the core and they are always present and independent of the load situation. Hysteresis loss is proportional to the enclosed area of the hysteresis loop of the used core material. Different materials have different hysteresis loops with bigger or smaller enclosed area. However it must take into account that a material with a hysteresis loop with a smaller enclosed area has higher production costs. Therefore it will not only reduce the hysteresis losses, the material costs will also increase. The electrical designer has to calculate which cost factor has the bigger impact on the offer and is more important.[13]

Generally the hysteresis loss can be calculated with following equation

$$P_h = k_h \cdot f \cdot B^n$$

P_h … Hysteresis loss
k_h … constant depending on the material
f … operating frequency
B … magnetic flux
n … Steinmetz constant

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[12] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, Chapter 14 Page 447

[13] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, Chapter 14 Page 448-451

The second part is the eddy current losses. Due to the time variation of the flux and the fact that the core material is conductive a voltage will be induced and a circulating current is flowing in a closed path. The magnitude of the eddy current is defined by the resistance and the length of the path. Beside of the losses eddy currents are also responsible for the noise of the transformer. Higher eddy currents lead to louder noise and therefore it is also better to reduce the eddy currents. To reduce the current the core will not be built by one piece of metal it will be made from stacked thin lamination layers. The resistance increases, the length of the path decreases and instead of one big eddy current you get a sum of small eddy currents and the total amount of the eddy current losses decreases.[14]

Generally the eddy current losses can be calculated with following equation

$$P_e = k_e \cdot f^2 \cdot t^2 \cdot B^2$$

P_e	… eddy current losses
k_e	… constant depending on the material
f	… operating frequency
B	… magnetic flux
t	… thickness of individual lamination

With the exception of the operating frequency the electrical designer has some possibilities to reduce the no load losses. Better core material with a smaller hysteresis loop will decrease hysteresis loss. The use of thinner core steel laminations with higher resistances will decrease eddy current losses as well. More winding turns for the same volts per turn will give the possibility to reduce the magnitude of the magnetic flux or to reduce the core area and it will lead to lower no load losses otherwise as we will see this point will increase the load losses. In general all this possibilities are a question of the electrical designer and depends of the loss evaluation, site or transport restrictions and many more.[15]

2.2.2 Load losses

“The load loss of a transformer is that proportion of the losses generated by the flow of load current and which varies as the square of the load current.
This falls into three categories:

- Resistive loss within the winding conductors and leads.
- Eddy current loss in the winding conductors.
- Eddy current loss in the tanks and structural steelwork.”[16]

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[14] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 3 Page 89

[15] P. P. Douglas, "Energy efficiency cost of losses," in *ZA Transformer Day,* 2013,

[16] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, Chapter 3 Page 53

The resistance is proportional to the conductor length divided by the conductor area. The electrical designer has the possibility to reduce the I^2R losses by reducing the resistance because the current is defined by the load situation. Reducing the winding turns to reduce the load losses with constant volts per turn would lead to higher no load losses because of the higher magnetic flux which is needed. To reduce the eddy currents which come from the induced voltage in the conductors due to the leakage flux, the resistance must be increased. There are two possibilities available to increase them, one is to reduce the cross sectional area of the conductor but this will produce higher I^2R losses or to subdivide the conductor into strips, to reduce the length of the path for the eddy currents and split it into many small eddy currents instead of one big current. For conductors with one big cross sectional area also the skin effect will come into account and will increase the resistance. Eddy current losses in the tanks also come from the leakage flux but they are only a little part of the total load losses.[17]

2.3 Conductors

Now we will move on to the active part of a transformer. In general the core and the windings will build the active part of the transformer. However sometimes also pressed parts, tap changer and connecting cables count to the active part. Here we will only take a look to the windings, the core and later (chapter 3) on the tap changers.

The conductors are the main parts of the windings. They are carrying the current and as combination of many of them they are wounded around the core as winding. The conductors are paper or enamel covered. Paper has the advantage that it is always available and cheap. The strips of a multi strip conductor can be bonded together with epoxy to increase the mechanical strength. For high current conditions the paper cover is replaced by net cover for better cooling condition. Conductors normally made from copper but also aluminium could be used. Aluminium is cheaper and lighter but to carry the same current you need a bigger cross section and copper can handle mechanical stresses much better. Some important Parameters for the calculation are the conductor current density **J** which lies in between two and four A/mm^2 and the space factor which is defined by the proportion of active copper to the overall volume of the conductor and depends on the conductor current density. Electrical designers try to get the space factor as high as possible but subdividing the conductor into strips for reducing the load losses will decrease them. The thickness of the conductor insulation depends on the voltage between the turns and the current to allow optimal cooling conditions. The conductors have a rectangular cross section instead of a circle cross section, to use the free space of the window area as good as possible to get the best possible space factor. To avoid high electrical stress the conductors are not allowed to have sharp edges.[18]

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[17] J. J. Winders Jr., *Power Transformers Principles and Applications.* Marcel Dekker, 2002, Chapter 3 Page 86-88

[18] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 1 page 2

2.3.1 Single Strip Conductors

This is the simplest Conductor type. It is used for low current for example for the HV-winding and they are paper covered. For high currents it would be uneconomic to use one conductor with a big cross section because of the increasing eddy current losses as explained above. However additional axial or radial stray losses produced by the leakage flux are important. For higher currents it is necessary to use some conductors in parallel, the so called twin or triple strip conductors.

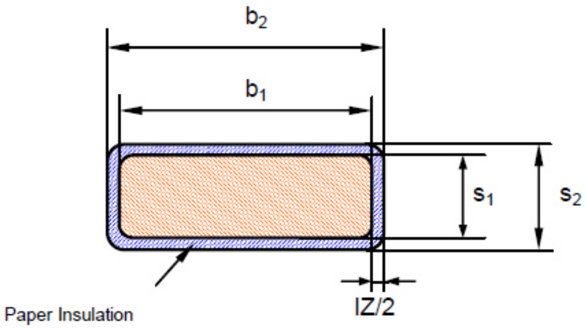

FIGURE 2.3.1-1 SINGLE STRIP CONDUCTOR[19]

2.3.2 Twin/triple Strip Conductors

Twin or triple strip conductors are used for higher currents. Two or three conductors are used in parallel and would replace one big single strip conductor. Every strip is paper insulated and to increase the mechanical strength of the conductor there is also enamel insulation between the strips and the outer paper insulation represents the turn-to-turn insulation, this results in a lower space factor compared to a single strip conductor. To split a single strip in a multi strip conductor results in a lower mechanical strength of the conductor. An advantage of the new conductors is the reduced eddy current losses compared with a big single strip which is explained in 2.2. This means the height and the width of the winding rises and it would not be possible to make an efficient winding design. The next step in the conductor technology is a CTC.

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[19] (16.05.2015). *Insulated Conductors*. Available: http://www.asta.at/products.php?lang=de&sub=3

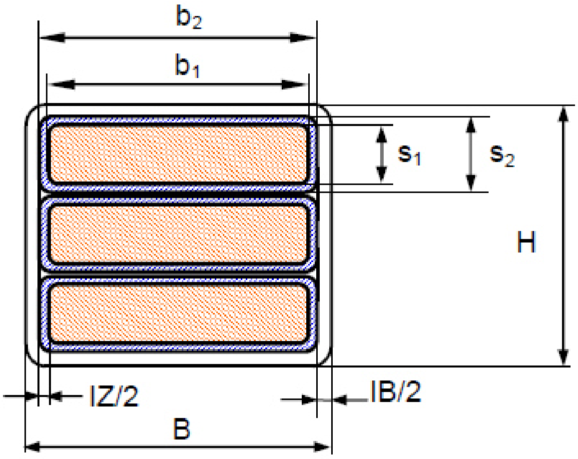

FIGURE 2.3.2-1 TRIPLE STRIP CONDUCTOR[20]

2.3.3 CTC

A Continuous Transposed Conductor consists of many strips to reduce the eddy current losses and they are insulated to each other. Without transposing the strips, the strips would have different induced voltage magnitudes. Different induced voltage magnitudes between the strips produce a circulation current between them. To avoid them it is necessary to transpose the strips to each other inside the conductor. So it is not necessary to transpose the whole conductors and reduces the winding time. It must be mentioned that more strips would increase the costs for such conductor types.[21]

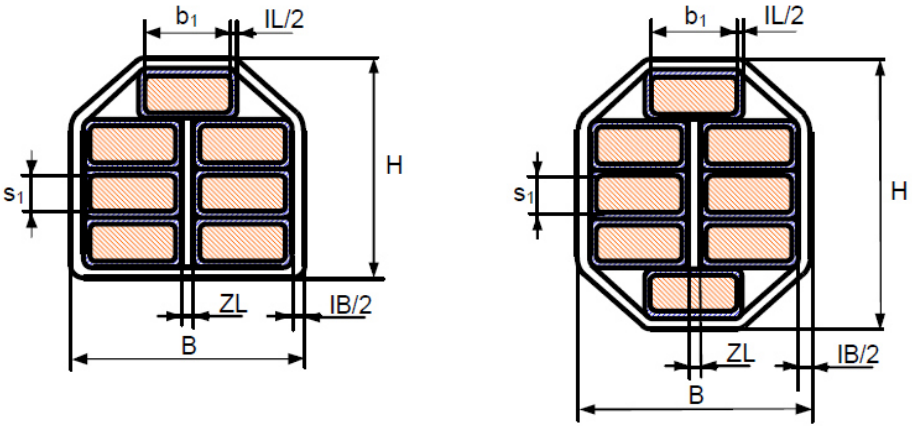

FIGURE 2.3.3-1 TYPES OF A CTC[22]

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[20] (16.05.2015). *Insulated Conductors*. Available: http://www.asta.at/products.php?lang=de&sub=3

[21] Martin J. Heathcote, CEng, FIEE, The J & P Transformer Book. Oxford: Newnes, 1998, Chapter4 Page 126-127

[22] (16.05.2015). *CTC*. Available: http://www.asta.at/products.php?lang=de&sub=1

2.4 Windings

The next step would be to wound the conductors around the core and we get the winding.
The used winding technology depends on:

- Manufacturing costs
- Max. short circuit forces
- Dimensional restrictions
- Loss evaluation

The required insulation between the windings will be discussed in 2.6, but inside the windings the layers and discs have different voltages and therefore an insulation between them is required. Inside a winding the insulation between layers or discs consists of paper, pressboard and oil. The oil flows in axial and/or radial cooling ducts and is responsible for the heat transfer.

2.4.1 Layer Winding

They are used for low-voltage and for a small number of turns. They wound helical around the core so this type is also called a "Helical Winding". The electrical designer has the possibility to occupy the maximum axial length of the core with the total number of turns to reduce the short circuit impedance if it is required to full fill the customer requirements. The ordinary setup between the core and the winding is depending on the magnitude of the electrical field and axial cooling ducts are considered. When there are too many turns for a single Layer, the winding consists of multi Layers. Therefore an axial insulation between the layers is necessary. This insulation consists of paper which is covered with oil for better insulation. For a high-voltage winding with much more turns compared to the low-voltage winding more layers would be needed and between every layer an insulation is also needed and more layers would have a negative effect on the mechanical strength of the whole winding.[23]

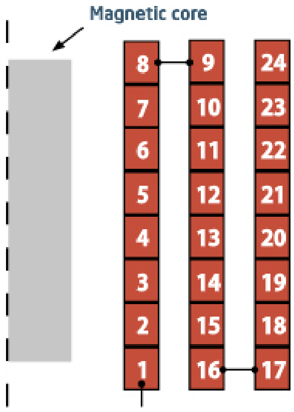

FIGURE 2.4.1-1 LAYER WINDING[24]

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[23] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, Chapter 4 Page 125

[24] M. B. Jean Sanchez, "Basics of Transformers," *Transformers Magazine,* vol. 1, pp. 12-15, 2014.

As you can mention from the figure the insulation between turn 8 and 9 only must be designed for 1x the voltage per turn but between turn 1 and 16 it must be designed for 8x the voltage per turn. This means that the insulation between two layers has not the same thickness over the whole length. More and more layers will have the disadvantage that due to the skin-effect which will increase the resistance and the proximity-effect which will act between the layers the losses will increase. Therefore it is better to use a disc-winding for the high voltage.

2.4.2 Disc Winding

In a disc winding the turns wound radial from the core to the outside to form a disc. The turns of a disc are insulated to each other for the voltage per turn. Every disc starts at the core and the connection between the discs is made from the last turn of the previous disc to the first turn of the actual disc. This means that at every point between the two discs is the same high voltage so that the insulation has the same thickness over the whole length. A disadvantage is that a long joint is needed to connect the discs. A further development is a continuous disc winding. It starts like a normal disc winding but after the first disc, the second does not start above the first. The next disc always starts over or under the last turn of the last disc.[25]

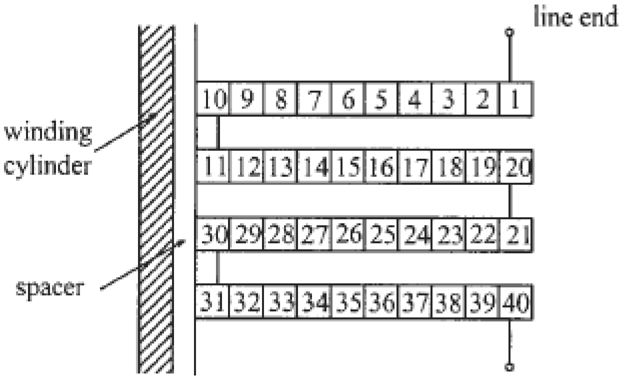

FIGURE 2.4.2-1 CONTINUOUS DISC WINDING[26]

To withstand impulse voltages the voltage stress of the windings needs to be determined. Therefore the impulse voltage distribution must be calculated. At the beginning when a step voltage is applied to the winding only capacitances responsible for the initial voltage distribution. It depends on the ratio α between the parallel capacitance and the series capacitance. After a sufficient time the winding inductances will affect the voltage distribution and the final voltage distribution will be linear. Because of the different initial and

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[25] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, Chapter 4 Page 128-129

[26] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 7 Page 284

final distribution a transient process is taking place and this transient is oscillating around the final distribution. The maximum values of this oscillating voltage are represented with curve (c). To keep the stress for the winding and the maximum voltage as low as possible the difference between initial and final distribution should be as low as possible. This can be managed by making α as low as possible by varying the capacitances. The series capacitance consists of the capacitance between turns and capacitance between discs. The parallel capacitance consists of the capacitance between windings and the capacitance to the ground. It is easier to vary the series capacitance then the parallel capacitance.[27]

Ratio between series capacitance and parallel capacitance:

$$\alpha = \sqrt{\frac{C_P}{C_S}}$$

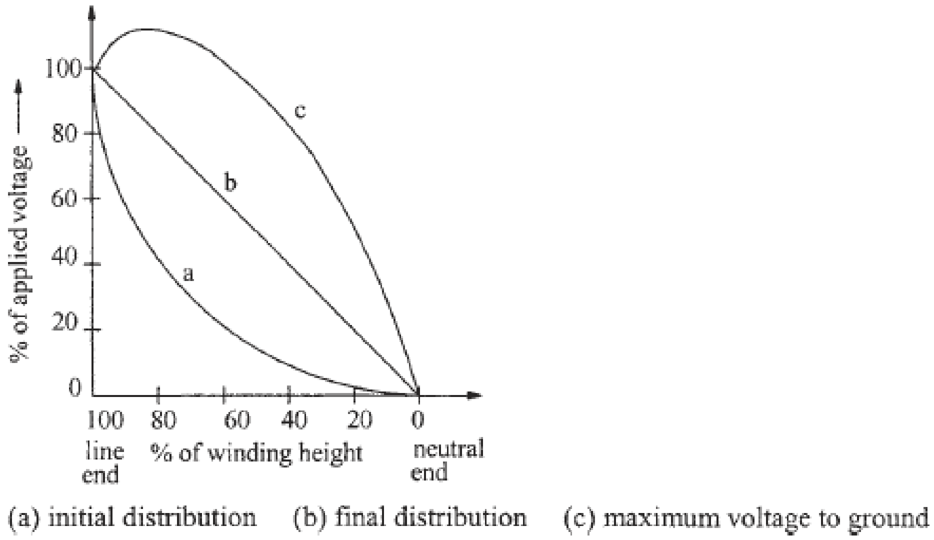

FIGURE 2.4.2-2 IMPULSE VOLTAGE DISTRIBUTION[28]

Increasing the series capacitance is possible with the next technology step, by using an interleaved continuous disc winding. The principle is to increase the series capacitance of the winding by separating two consecutive electrical turns with one turn which is electrically much farther along the winding. A disadvantage could be that the insulation between two adjacent turns must withstand a working voltage which is equal to the turns per disc times the voltage per turn because in a not interleaved winding it is only the voltage per turn. If a turn has more than one parallel conductor, not only the turns have to be interleaved also the

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[27] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 7 Page 277-281

[28] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 7 Page 278

conductors but this will increase the manufacturing effort. A better solution which also increases the series capacitance is a shielded winding.[29]

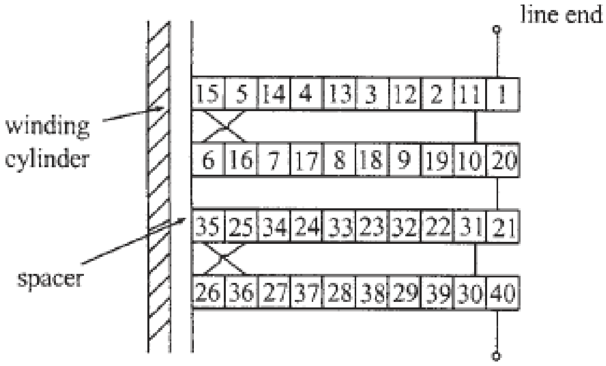

FIGURE 2.4.2-3 INTERLEAVED WINDING[30]

2.4.3 Compact Winding

Another common winding type is the compact winding. It is a disc winding with axial cooling ducts without pressboard radial spacers. Therefore the shrinkage of the winding is less and it results in a better short circuit withstand capability and better load noise performance. The axial cooling ducts are made with a clack band and there width is independent of the axial clamping pressure to allow perfect axial cooling ducts. Without radial spacers the series capacitance will increase and the compact winding will give a better voltage distribution compared to a disc winding. Maybe shielding or interleaving is not necessary and the costs and manufacturing time can be reduced.

2.5 Core

From the windings now to the core. The core is the biggest part of a transformer it carries the windings and gives the main flux his path. He consists of limbs which carry the windings and yokes which connect the limbs but do not carry any windings. In 2.2.1 it was mentioned that the core does not consist of one big piece of metal because of the eddy current losses. He is made from thin lamination layers. To avoid sharp edges for better placing the windings around the core and to protect the insulations the form of the core is cylindrical. The electrical designer has the possibility to reduce the core losses and the noise level by choosing a better core material. At the moment the most common material is grain oriented electrical steel GOES. Grain oriented means that the magnetic domains in the steel orientated in one direction and this will decrease the core losses when the magnetic flux follows this direction.

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[29] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 7 Page 284

[30] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, Chapter 7 Page 284

To reduce the cost for building a core, it is normal that a transformer factory has only some predefined widths for layers. It is the reason why it is not possible to build a core with an exact cylindrical cross section with the layers you get a stepping. Therefore the geometrical utilisation factor η was defined. This factor is the relation between the real cross section compared to a cylindrical cross section. The maximum value for the factor η_{max}=0.9575 but therefore you need more than 10 layer with different thickness which become uneconomic and will increase the costs especially the storage costs for the layers. Small cores do not need any pin to fix the layers together. This is made by the first winding which is wound around the core and put the layers together. For bigger cores pins are needed to fix the layers together. Cores need some cooling slots which will reduce the geometrical utilisation factor too. The cooling slots could insert parallel or vertical to the layers. Parallel layers are easier to insert but they are not very efficient and you need more of them, vertical slots are more efficient but it is more difficult to insert them. Because of a thin non-conducting insulation on the layers, there is also the lamination factor of a core f_{FE} which is the ratio of the lamination to the total area (insulation plus lamination) of the layer and is about 0.96.[31]

Therefore the real cross section is:

$$A_{eff} = \frac{\pi}{4} \cdot D^2 \cdot \eta \cdot f_{FE}$$

In general the formula can be simplified to:

$$A_{eff} = 0.7 \cdot D^2$$

The figure shows the principle building of a core without any cooling slots and pins.

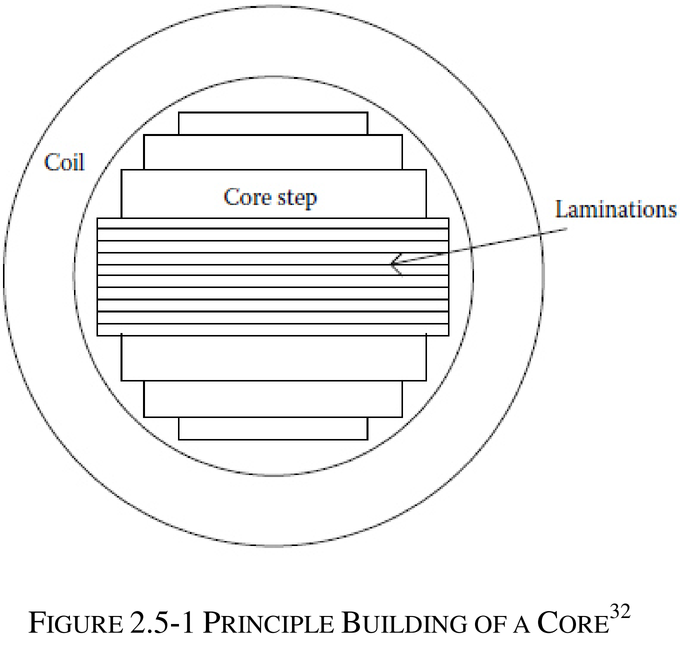

FIGURE 2.5-1 PRINCIPLE BUILDING OF A CORE[32]

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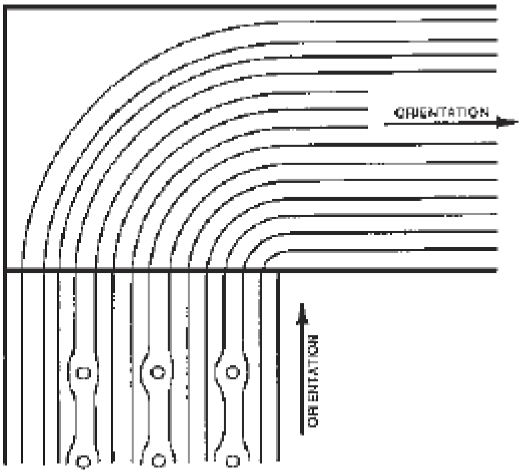
[31] R. Küchler, *Die Transformatoren.* 1956, chapter 9 page 265-267

[32] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, chapter 1 page 10

Grain oriented electrical steel has the advantage that the flux follows the orientation direction which leads to lower core losses. A disadvantage is that if the flux deviates from this direction the core losses will significantly increase. This happens at the corners of the core or at holes for example for bolts inside the core. The easiest way to connect the limb and the yoke at the corner is in an angle of 90° but to limit the deviate of the orientation it is better to connect them in a 45° mitre (figure 2.5-2 and 2.5-3). And the different layers at the corners must be overlapped to avoid that the flux goes across the air from the limb to the yoke instead of the direct path. There are two main concepts for setting joints. The standard method alternates the gap between limb and yoke sheet. The effective reduction of magnetic circuit cross section will be 50%. The other one is the step lap technology (figure 2.5-4), it delocalize gaps to 6 different places. The effective reduction of cross section area is 1/numbers of steps which will have lower losses. It is possible to use more steps to decrease the core losses but this will increase the manufacturing costs, time and the complexity of the core. Bolt holes will increase the core losses transformer built boltless, the laminations hold together with insulated clamp bands or with the windings because they wound around the limb and hold the laminations of the limb together.[33]



(a) Square cut (bolted)

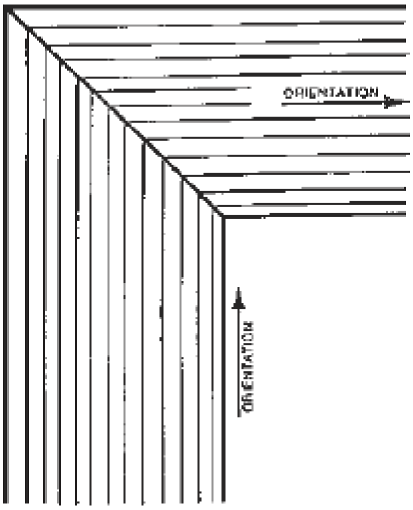


FIGURE 2.5-2 EFFECT OF HOLES AND CORNERS ON CORE FLUX[34]

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[33] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, chapter 4 page 108-115

[34] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, chapter 4 page 110

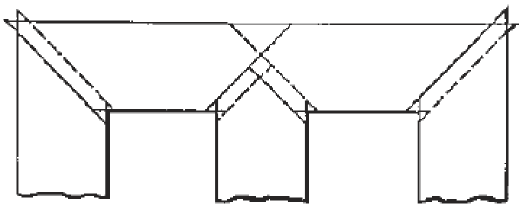

FIGURE 2.5-3 45° MITRE OVERLAP CONSTRUCTION[35]

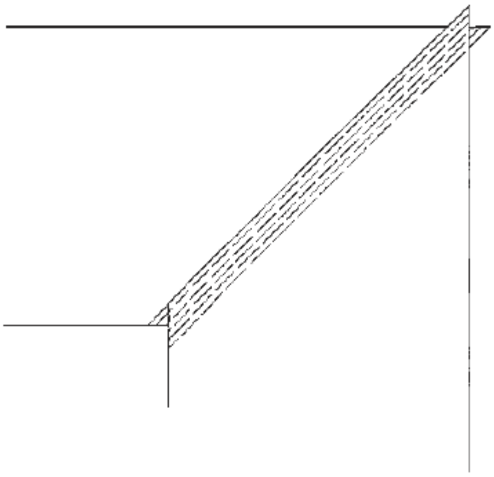

FIGURE 2.5-4 FIVE STEP LAPPED MITRED CORE JOINT[36]

For calculating the cross section of the core the designer has to choose a diameter of it. With this first diameter the cross section A_{eff} of the core and further the voltage per turn can be calculated. For calculating the voltage per turn VpT it is also necessary to choose the value of the magnetic field on which the transformer should operate. Therefore you have to look at the magnetizing curve of the core material and choose a value of B where the material is not driven into saturation. That's also an advantage of GOES because a B up to 2T is possible.

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[35] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, chapter 4 page 111

[36] Martin J. Heathcote, CEng, FIEE, *The J & P Transformer Book.* Oxford: Newnes, 1998, chapter 4 page 115

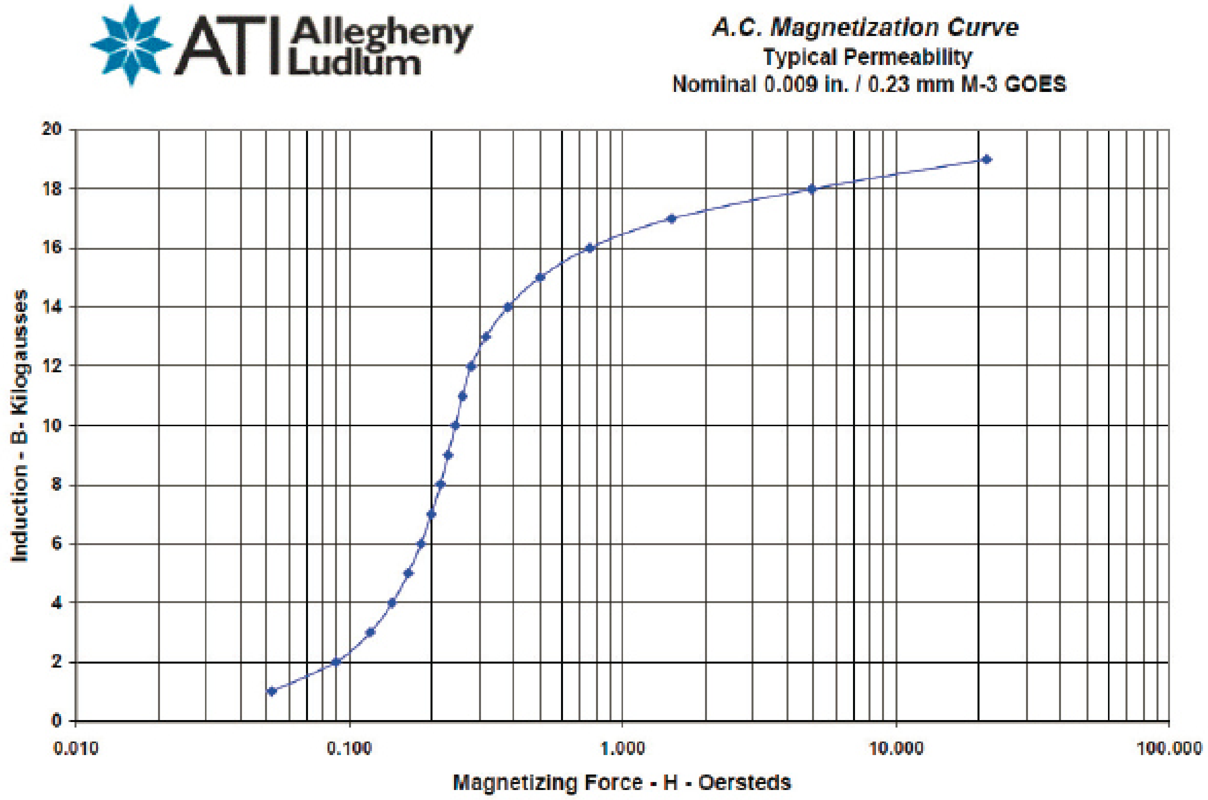

Figure 2.5-5 Magnetization Curve of GOES[37]

Now with the transformer universal EMF equation from chapter 2.1 ignoring the number of turns we can calculate the voltage per turn:

$$VpT = 4.44 \cdot f \cdot B \cdot A_{eff}$$

We can see if we want to change the VpT we can only change B or A_{eff} because the frequency is given by regional requirements. By changing B we must take into account that the no load losses, sound level also varies with B, and the saturation level of the core material. Therefore it is better, do not choose a B near saturation because regulation with variable flux (will be explained in chapter 3) can drive the core into saturation and the overload requirements should happen without saturation of the core.

The next step is to calculate the turns for the primary- and secondary side with the VpT. It is possible to compare the prices for copper and the core material to reduce the costs by using more or less of one material and now the load losses can be calculated. With the capitalization factors for the different losses they can be compared with each other. The electrical designer gets the possibility to reduce the losses by varying VpT but it should take into account that VpT should not become too high because a higher VpT needs a bigger turn to turn insulation and so the full winding needs more space and the costs for the insulation increases. This design process is an iteration process between the different losses and the price for copper and

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[37] (11.05.2015). *GOES datasheet*. Available: https://www.atimetals.com/products/Pages/grain-oriented-electrical-steel-goes.aspx

the core material. The companies have different ways and equations to find an initial diameter.

Generally there are two types of core, the core-form and the shell-form transformer. Every type needs different manufacturing machines therefore the transformer manufacturer decides which type of core they will produce. These types can be built with unwound limbs or not.

2.5.1 Types of Core

The main difference between those two types is shown in the following figure. In the core-form the winding surround the core and in the shell-form the core surround the winding.

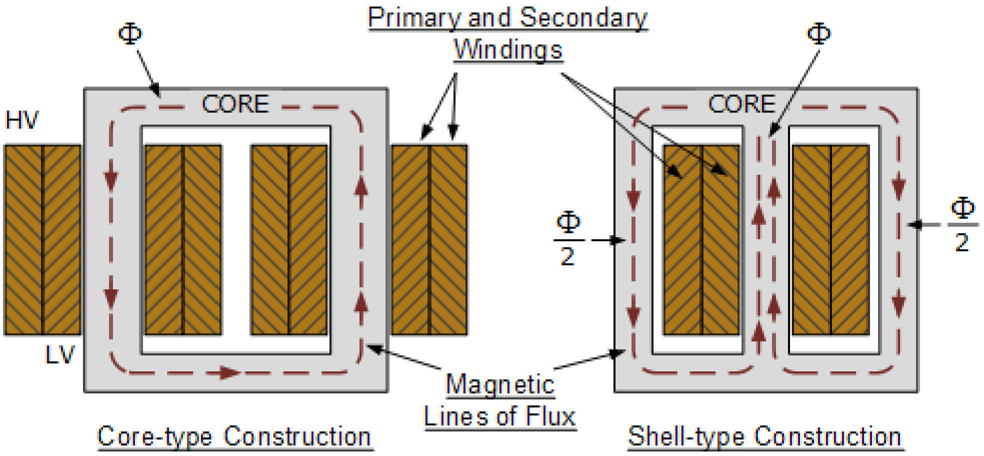

FIGURE 2.5.1-1 TYPES OF CORE[38]

For the core-form normally layer windings preferred because of the better ability to withstand short circuit forces. For the shell-form the windings can be disc windings because outside of the windings are the two limbs they give the windings extra mechanical strength. In figure 2.5.1-1 is shown that in the core-type the flux has only one return path, therefore the cross sections of the yokes and the limbs must be the same. The shell type has the advantage that the flux has two return paths over both unwounded limbs and therefore the cross sections of the unwounded limbs and yokes must only be 50% of them of the middle limb which carries the windings. The same cross section reductions are possible with a five limb core type transformer. Therefore it is possible to reduce the height and the weight of the transformer with a shell-type and a core-type too. Often the core construction depends on the manufacturing limitations. Companies are limited in weight and dimension of the transformers. It is possible to build three single phase transformer instead of one three phase transformer. One three phase unit will be cheaper than three single phase units but from the maintaining side if there is a fault in one phases it will be easier and cheaper to replace only a single phase unit. In figure 2.5.1-2 are different core- and shell types depending on single- or

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[38] (11.05.2015). *Transformer core construction*. Available: http://www.electronics-tutorials.ws/transformer/transformer-construction.html

three-phase. (a) is a single-phase shell-type transformer compared to (b) which is a single-phase core-type, (a) has reduced cross sections for the unwounded limbs and the yokes. (c) shows a single-phase four limb shell-type core with reduced height. Now from the single to the three-phase transformer. (d) shows a three-phase, three limb core-type transformer. The disadvantage of this construction is the unequal length of the magnetic path for the outer phases compared to the middle phase and this leads to different exciting currents and produces higher no load losses. To reduce the height of a three-phase transformer type a five limb core-type (e) is used instead of a three limb. (f) shows a three phase shell type transformer.

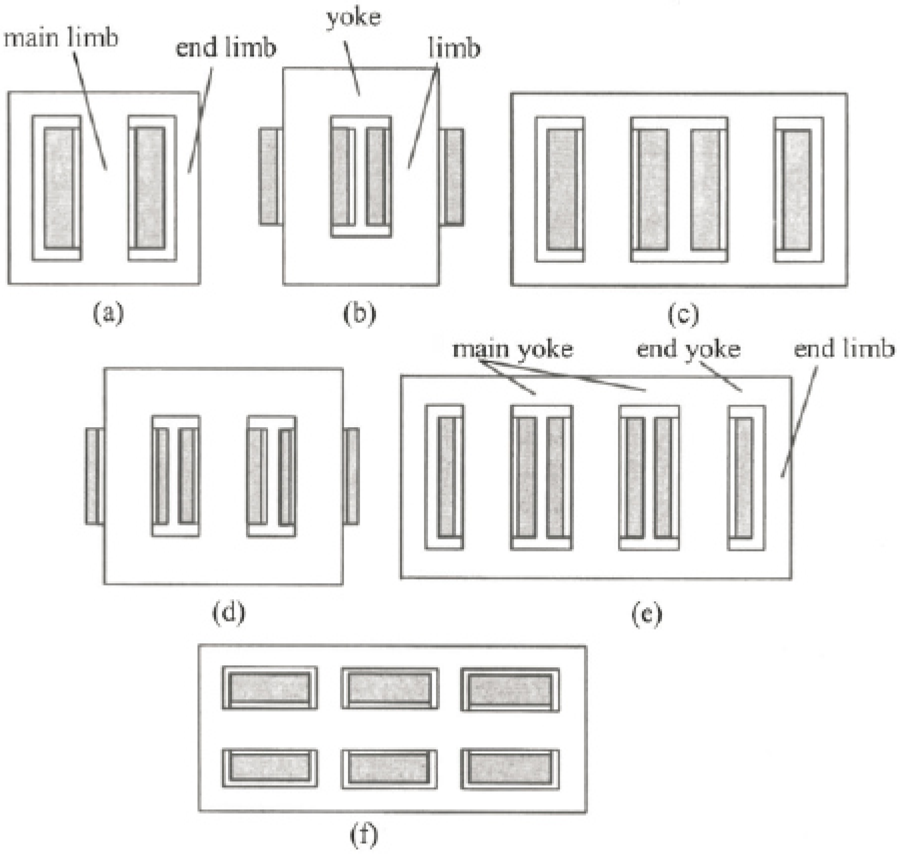

FIGURE 2.5.1-2 DIFFERENT TYPES OF CORE[39]

2.6 Insulation

The last part of a transformer which will be discussed is the insulation. Insulation can have a major impact on the transformer cost and with the space for the insulation it will affect the designing procedure of the active part, the core-type and the winding-type. Therefore electrical designers try to reduce the needed insulation space to reduce weight and costs. Insulation has the function to protect the active part of the transformer against the operating

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[39] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 2 page 37

voltages and overvoltages. Generally the insulation in a transformer can be categorized into two types. The major insulation is between the windings, the windings and yoke/limb and between high voltage leads and ground. The minor insulation is the internal insulation of the windings such as inter-turn and inter-disc insulation.[40]

2.6.1 Materials

Generally materials for the insulation can be classified into liquid insulation material and solid insulation material. It would be possible to fill pages of pages only with informations about these materials but that is not the main topic of this thesis and therefore I only will give a short overview about the main materials and there characteristics.

The liquid material is not only responsible for insulation and to fill in holes in the solid insulation it is also responsible for heat transfer. There are three main groups of liquids, mineral oils, with a $\varepsilon_r=2.2$, they are differentiated between uninhibited and inhibited mineral oils. The next ones are ester fluids, with a $\varepsilon_r=3.3$, differentiated between synthetic and natural fluids. The last ones are silicone fluids, with a $\varepsilon_r=2.7$. Mineral oil is the most common used insulation material because of his price and performance for example the highest breakdownvoltage compared to the others. Ester fluids and silicone fluids generally only used when special performance required which mineral oil will not full fill. Ester fluids have the advantages to mineral oil: no hazard to water, high flash point, superior oxidation stability. Disadvantages are higher cost and higher viscosity. Silicone fluids have the advantages to mineral oil: high flash point, self-extinguishing. Disadvantages are high cost, poorer dielectric strength on long gap distances. These liquid materials undergo a thermal expansion therefore expansion tanks on the transformer are required.[41]

The solid insulation materials are not only used for minor insulation, they are used in major insulation subdivide the gap for the liquid insulation from one long gap into many short gaps. Solid materials are paper, with a $\varepsilon_r=4.4$, which is cheap everywhere available. Pressboard with a $\varepsilon_r=4.2$, which is a thick insulation made from a number of paper layers. The last one is non-cellulosic material which is resistant to much higher temperatures (up to 220°C).[42]

2.6.2 Design insulation level

The insulation must be designed for the operating voltage and to withstand overvoltages. The average voltage stress on the insulation is decided by the electrical designer and varies for

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[40] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 8 page 327-328

[41] A. Küchler, *Hochspannungstechnik.* Springer, 2009, chapter 5 page 287 - 295

[42] A. Küchler, *Hochspannungstechnik.* Springer, 2009, chapter 5 page 298 - 306

different manufacturers but lies around 6kV/mm and here we will take 6kV/mm for the further calculations.

“The overvoltages can be broadly divided into lightning overvoltages (aperiodic surges with duration of one to tens of microseconds), switching overvoltages (oscillatory surges with duration up to thousands of microseconds), and temporary overvoltages (lasting for few minutes) at or close to the power frequency. The standards on transformers have defined voltage test levels for various voltage classes of transformers. There are basically four different types of tests, viz. lightning impulse test, switching impulse test, short duration power frequency test and long duration power frequency test with partial discharge measurement.”[43]

Depending on the highest voltage for equipment winding in the following table IEC 60076-3 are defined voltage test levels for lightning overvoltages and switching overvoltages.

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[43] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 8 page 348

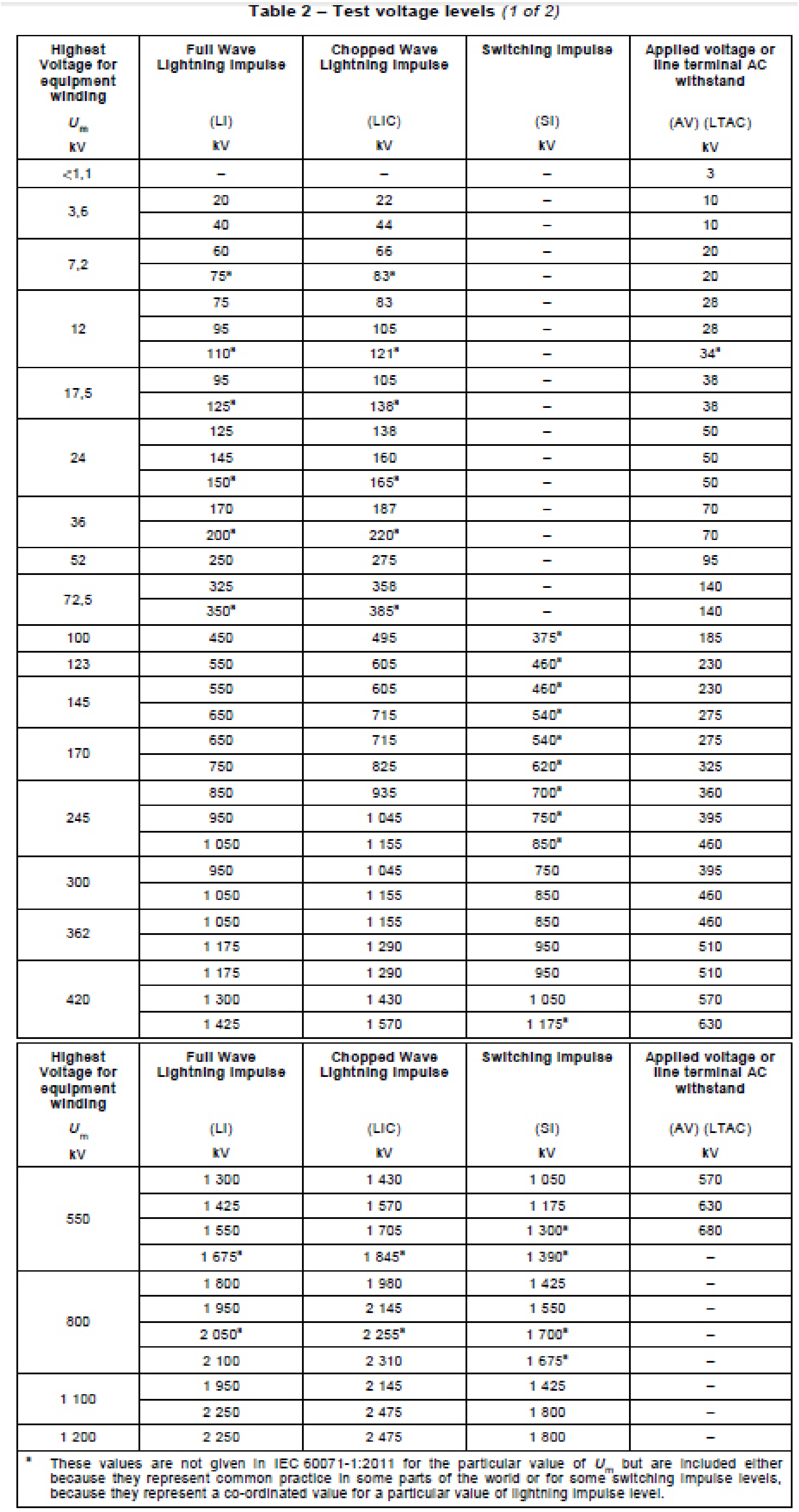

Table 2 – Test voltage levels *(1 of 2)*

Highest Voltage for equipment winding U_m kV	Full Wave Lightning Impulse (LI) kV	Chopped Wave Lightning Impulse (LIC) kV	Switching Impulse (SI) kV	Applied voltage or line terminal AC withstand (AV) (LTAC) kV
<1,1	–	–	–	3
3,6	20	22	–	10
	40	44	–	10
7,2	60	66	–	20
	75[a]	83[a]	–	20
12	75	83	–	28
	95	105	–	28
	110[a]	121[a]	–	34[a]
17,5	95	105	–	38
	125[a]	138[a]	–	38
24	125	138	–	50
	145	160	–	50
	150[a]	165[a]	–	50
36	170	187	–	70
	200[a]	220[a]	–	70
52	250	275	–	95
72,5	325	358	–	140
	350[a]	385[a]	–	140
100	450	495	375[a]	185
123	550	605	460[a]	230
145	550	605	460[a]	230
	650	715	540[a]	275
170	650	715	540[a]	275
	750	825	620[a]	325
245	850	935	700[a]	360
	950	1 045	750[a]	395
	1 050	1 155	850[a]	460
300	950	1 045	750	395
	1 050	1 155	850	460
362	1 050	1 155	850	460
	1 175	1 290	950	510
420	1 175	1 290	950	510
	1 300	1 430	1 050	570
	1 425	1 570	1 175[a]	630
550	1 300	1 430	1 050	570
	1 425	1 570	1 175	630
	1 550	1 705	1 300[a]	680
	1 675[a]	1 845[a]	1 390[a]	–
800	1 800	1 980	1 425	–
	1 950	2 145	1 550	–
	2 050[a]	2 255[a]	1 700[a]	–
	2 100	2 310	1 675[a]	–
1 100	1 950	2 145	1 425	–
	2 250	2 475	1 800	–
1 200	2 250	2 475	1 800	–

[a] These values are not given in IEC 60071-1:2011 for the particular value of U_m but are included either because they represent common practice in some parts of the world or for some switching impulse levels, because they represent a co-ordinated value for a particular value of lightning impulse level.

FIGURE 2.6.2-1 TEST VOLTAGE LEVELS (IEC60076 PART 3)[44]

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[44] "Power Transformer Part 3: Insulation levels, dielectric tests and external clearances in air," *IEC 60076-3:2000 Edition 2. 0 2000-03,* 2000.

Let’s take a 220kV/110kV transformer. Therefore from the table we get:

HV		LV	
U_{1LL}	220kV	U_{2LL}	110kV
U_m	245kV	U_m	123kV
Full wave lightning impulse (BIL)	1050kV	Full wave lightning impulse (BIL)	550kV
Switching impulse (SIL)	850kV	Switching impulse (SIL)	460kV

TABLE 2 TEST VOLTAGE LEVELS FOR GIVEN TRANSFORMER

Nevertheless these are different voltage levels to calculate the thickness of the needed insulation it is better to have only one voltage level. It is better to transform them into an equivalent voltage, the one minute short duration power frequency voltage and calculate the insulation with the maximum equivalent voltage. This equivalent voltage is called Design insulation level (DIL). To calculate this voltage, multiplication factors are needed, they are shown in the following table.

Test voltage	Multiplication factor
Full wave lightning impulse level (BIL)	~(1/2.30)=0.44
Switching impulse level (SIL)	~(1/1.80)=0.55
Long duration (one hour) power frequency voltage	~(1/0.80)=1.25

TABLE 3 MULTIPLICATION FACTORS FOR THE EQUIVALENT VOLTAGE[45]

The multiplication factors from different manufacturers can vary in a narrow range around these values.

In our example with the multiplication factors for the high voltage winding we get the maximum DIL = 467.5kV and for the low voltage winding the maximum DIL = 253kV. The insulation between high voltage winding and low voltage winding must now withstand a DIL of 467.5kV and the insulation from the low voltage winding to the core must withstand a DIL of 253kV. With the defined voltage stress E=6kV/mm the thickness of the insulation between HV and LV will be:

$$d_{HVLV} = \frac{V}{E} = \frac{467.5kV}{6kV/mm} = 77.92mm$$

And the insulation between core and LV will be:

$$d_{CLV} = \frac{V}{E} = \frac{253kV}{6kV/mm} = 42.17mm$$

The breakdown strength of transformer oil depends on its stressed volume, insulation gap and the electrodes lamination. With an increasing volume and gap the breakdown strength will decrease. The following figure shows the breakdown strength of oil gaps in transformers. To

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[45] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 8 page 350

calculate the breakdown strength for different oil gaps the quality of the oil and the type of the electrodes must take into account.

$$E_d = \frac{E_0}{d^a}$$

For insulated electrodes and degassed oil (1)

$E_0 = 21 \frac{kV}{mm}$ $a = 0.37mm$

For insulated electrodes and gas saturated oil (2)

$E_0 = 17.8 \frac{kV}{mm}$ $a = 0.364mm$

For noninsulated electrodes and degassed oil (3)

$E_0 = 17.8 \frac{kV}{mm}$ $a = 0.364mm$

For noninsulated electrodes and degassed oil (4)[46]

$E_0 = 13.5 \frac{kV}{mm}$ $a = 0.375mm$

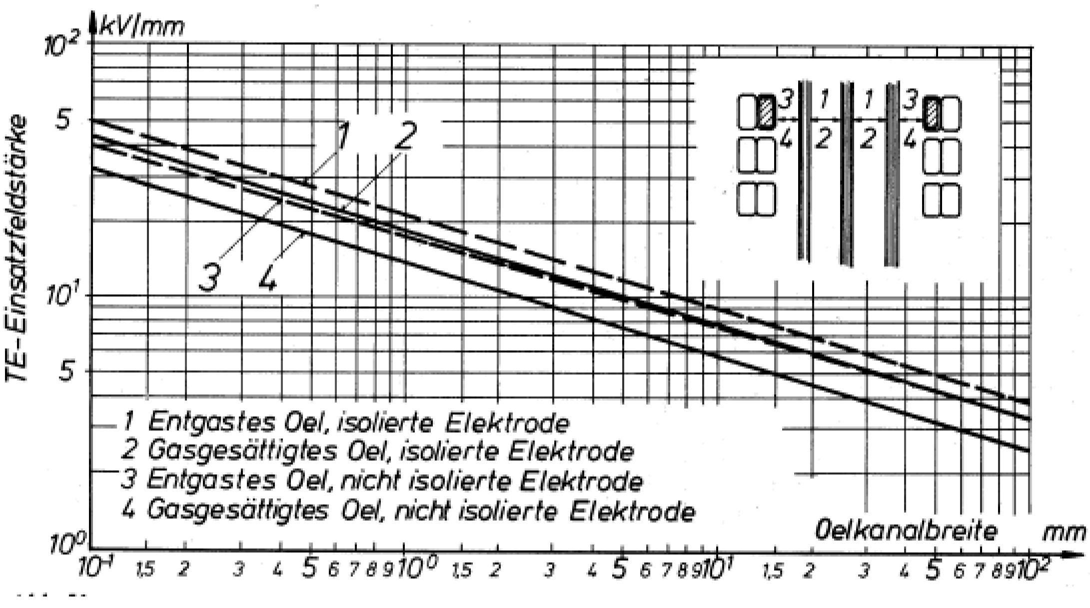

FIGURE 2.6.2-2 BREAKDOWN STRENGTH OF OIL GAPS[47]

As you can see the breakdown strength increases for shorter oil gaps. It is possible to decrease the insulation gap for the same DIL by dividing the gap from one big oil gap into many small oil gaps. This has the effect to decrease the stray gap of the transformer, the weight because less oil is needed, the dimensions of the transformer by decreasing the insulation gap and all

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[46] A. Küchler, *Hochspannungstechnik.* Springer, 2009, chapter 3 page 211

[47] H. P. Moser, Transformerboard. Rapperswill: H. P. Moser, H. Weidmann AG, 1979, chapter D page 52

this will reduce the costs for the transformer. The dividing is made with pressboard. The pressboard is used as barrier to divide the oil gap and it should be as thin as possible which is practical about 2mm for good mechanical stability. Now the insulation consists of two different materials with different relative permittivity. First let's take a look how the voltage stress deals with this situation on a simple example of a capacitor with a two material dielectric of mineral oil $\varepsilon_{r1}=2.2$ and pressboard $\varepsilon_{r2}=4.2$ with a quasi-stationary field.

The rms of the voltage over the dielectric equals

$$V = d_1 \cdot E_1 + d_2 \cdot E_2$$

The rms of the electric displacement field D will be

$$D = \varepsilon_{r1} \cdot E_1 = \varepsilon_{r2} \cdot E_2$$

The voltage stresses will be

$$\frac{E_1}{E_2} = \frac{\varepsilon_{r2}}{\varepsilon_{r1}}$$

This means that the voltage stress in the mineral oil will be about twice of that in the pressboard it is called "field displacement".

For a cylindrical arrangement with two concentric cylinders with radiuses r_1 and r_2 the field strength between them will be.

$$E(r) = \frac{V}{r \cdot ln\frac{r_2}{r_1}}$$

The maximum field strength is at r_1 and will be

$$E_{max} = \frac{V}{r_1 \cdot ln\frac{r_2}{r_1}}$$

Now it is possible to calculate the ratio between r_1 and r_2 that E_{max} become a minimum and an equal field distribution, this will be

$$r_1 = \frac{r_2}{e}$$

This can be used for a barrier system too, to optimize E_{max} between the solid and liquid insulation material.[48] But a barrier insulation system is limited by some factors. There should be a moderate number of barriers and a single oil gap should not have more than 12mm. For the minimum insulation gap with a given number of barriers the thickness of them should be as thin as possible. However this is limited by the manufacturing process and the demand of a given mechanical strength. Generally the lowest possible thickness is between 1.5 and 2 mm.

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[48] A. Küchler, *Hochspannungstechnik.* Springer, 2009, chapter 2 page 33-35

The insulation between two phases is also made from oil gaps and pressboard barriers but here are less pressboard barriers used and the oil gaps will be longer. This means that the breakdown strength per mm of the oil decreases and also the voltage stress in the pressboard but in sum it is possible to reduce the manufacturing time for the insulation and to reduce the costs for the insulation. The problem is that a longer oil gap will increase the possibility of a breakdown due to particles in the oil gap.

A special case is the end winding insulation where a lower average voltage stress is taken because of sharp corners of the core. It is also necessary to reduce the voltage stress at the winding ends with static end rings.[49]

3. Voltage Regulation for Transformer

After that overview of the transformer principles and the transformer design basics, now let's take a look at the voltage regulation for transformers. Voltage regulation is necessary wherever the load or the voltage varies. Transformers build with an extra tap winding where it is possible to add or subtract parts of this winding to the primary or secondary winding or the regulation is made with a tapped winding therefore no additional tap winding is needed. It is possible to connect the tap winding with other windings under load or no load conditions and there are different regulation types possible. First we take a look at the difference between on load tap changer OLTC and off load tap changer, so called de-energized tap changer DETC.

3.1 OLTC versus DETC

Tap changers are also count to the active part of a transformer. OLTC's are used where the voltage or the load varies frequently and where it is not possible to change the tap position under no load. DETC's are used where it is no problem to turn off the transformer and change the tap position and because of the fact the changing is doing by hand, where a changing is happen not very often. The following table compares OLTCs and DETCs and will show the differences.

OLTC	DETC
Wide voltage regulation range	Generally +-5% voltage regulation range
Change happens under load	Change happens under no load
Change happens automatically	Change happens by hand
Placed inside or outside the tank	Placed inside the tank
For high power, high voltage	For low power, low voltage

TABLE 4 CHARACTERISTICS OF OLTC AND DETC

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[49] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 8 page 352-358

To select a tap changer for the design some characteristics are needed and must compare with the datasheets of them.

The main characteristics are: maximum rated through current, maximum rated step voltage, maximum rated switching capacity, highest voltage for equipment, number of tapping positions, short circuit current and the initial symmetrical short circuit current

As mentioned OLTCs should not interrupt the load by changing the tap position, it is also called "make-before-break". To provide a short circuit between two tap positions during "the make process" two different principles can be used. One is the resistive switching and the other one is the reactive switching. At the beginning the switching or insulation medium for them has been oil but nowadays with a reduced fire hazard and the prevention of water pollution vacuum is becoming the new insulation and switching medium. Also there is contamination of oil during the arc because the oil is replaced by vacuum. The new vacuum switch is placed in a hermetically sealed switching chamber and is independent from the ambient medium but a loss of vacuum must avoid.

The resistive switching:

There are two different types of resistor OLTCs. One has only one selector switch which combines the function of the tap selector and the diverter switch (a). The other one has a separate tap selector and diverter switch (b).

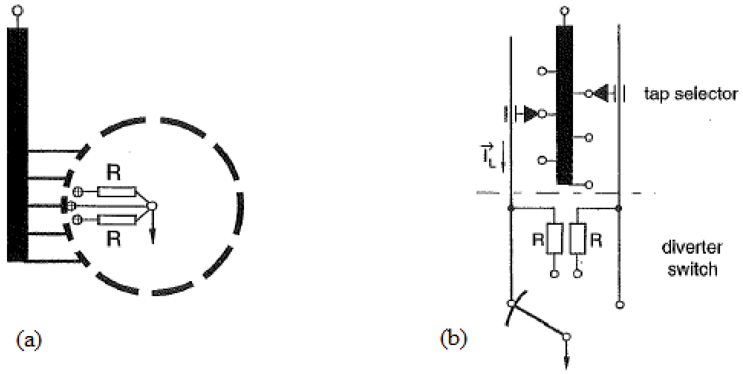

FIGURE 3.1-1 RESISTOR TYPE OLTCS[50]

The switching principle is for both the same and will be shown for the OLTC with separate tap switch, diverter switch and vacuum interrupters. He consists of two tap selector switches, one arc switch with four contacts and two resistors. Because of the short circuit between two taps during the "make process" the resistor is inserted to limit the short circuit current. Therefore the resistor must withstand the full load current plus the circulating current. The current over the resistor producing heat and $I^2 \cdot R$ losses. This type of OLTC is generally located inside the tank.

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[50] A. Krämer, *On-Load Tap-Changers for Power Transformers.* Spintler - Medienhaus Weiden, 2000, chapter 2 page 7

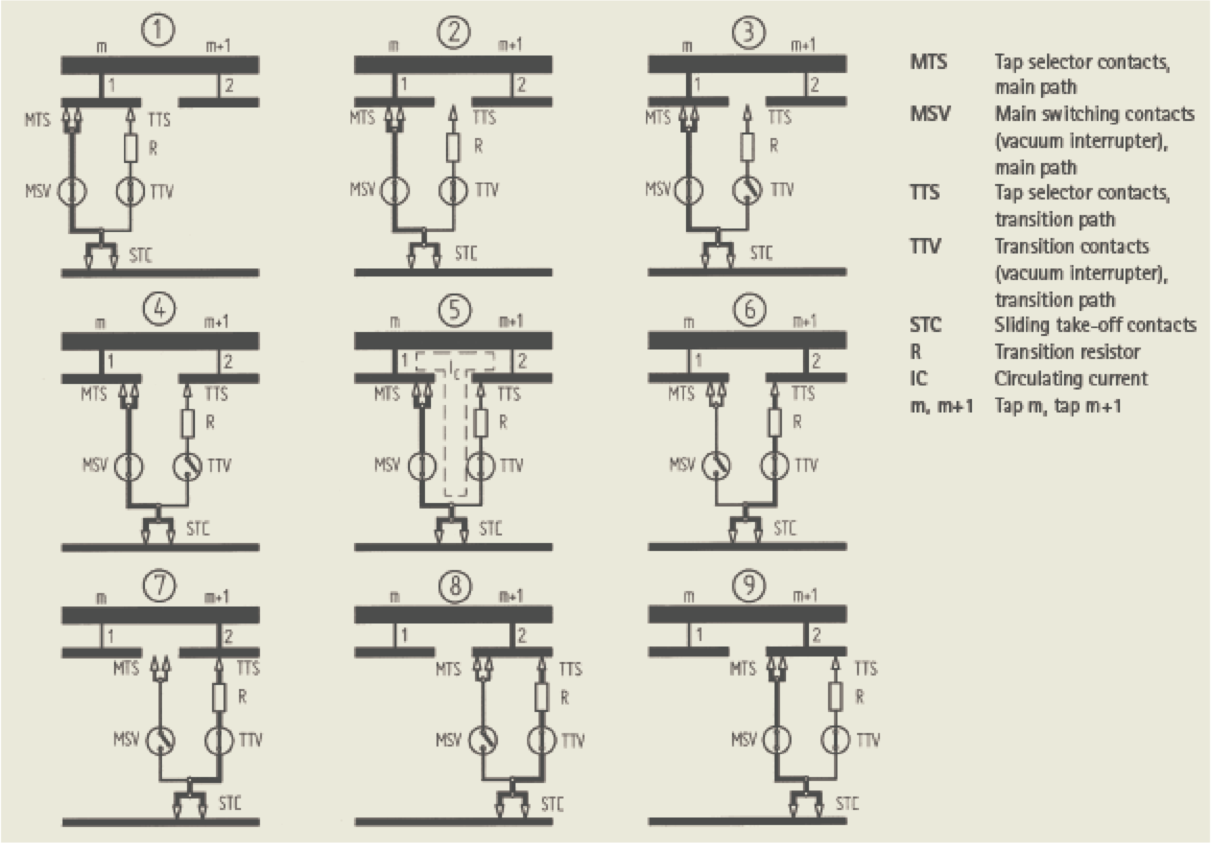

FIGURE 3.1-2 SWITCHING PRINCIPLE FOR RESISTOR VACUUM TYPE OLTC[51]

Step 1 is the active state where the load current flows over MTS. In step 2, TTS opens and the load current is still flowing over MTS. In step 3 TTV opens under no load. In step 4, TTS is moved to the new tap position. In step 5 TTV closes and a circulating current starts to flow limited by the resistor and the voltage difference between the taps flows. In step 6 MSV opens and the load current now flows over TTS and TTV. In step 7 and 8 MTS is moved to the new tap position. Finally in step 9 MSV is closed and the load current flows over them again.[52]

The reactive switching:

Instead of resistors reactances are used. They have the advantage do not dissipate so much energy and they use reactive energy which does not produce any heat. This type has two reactances, one tap changer with two selectors, one vacuum interrupter and two bypass switches. The non-bridging position is reached when the tap selector contacts located on different taps. The bridging position is reached when the tap selector contacts located on the same tap position. From a non-bridging position to a bridging position seven steps are needed and will be explained now. Step 1 shows a non-bridging position and the load current flows over both paths. In step 2 by-pass switch P3 opens, the current from P4 now flows over the

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[51] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013., chapter 4 page 17

[52] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013., chapter 4 page 17

vacuum interrupter. In step 3 the vacuum interrupter opens and the arc is over after first current zero. Step 4 and 5 show the movement to the new tap position. In step 6 the vacuum interrupter closes. In step 7 P3 closes the bridging position is reached and a circulating current flows limited by the reactances. To get from the bridging position in a non-bridging position steps 1-6 have to be done in the other direction. [53]

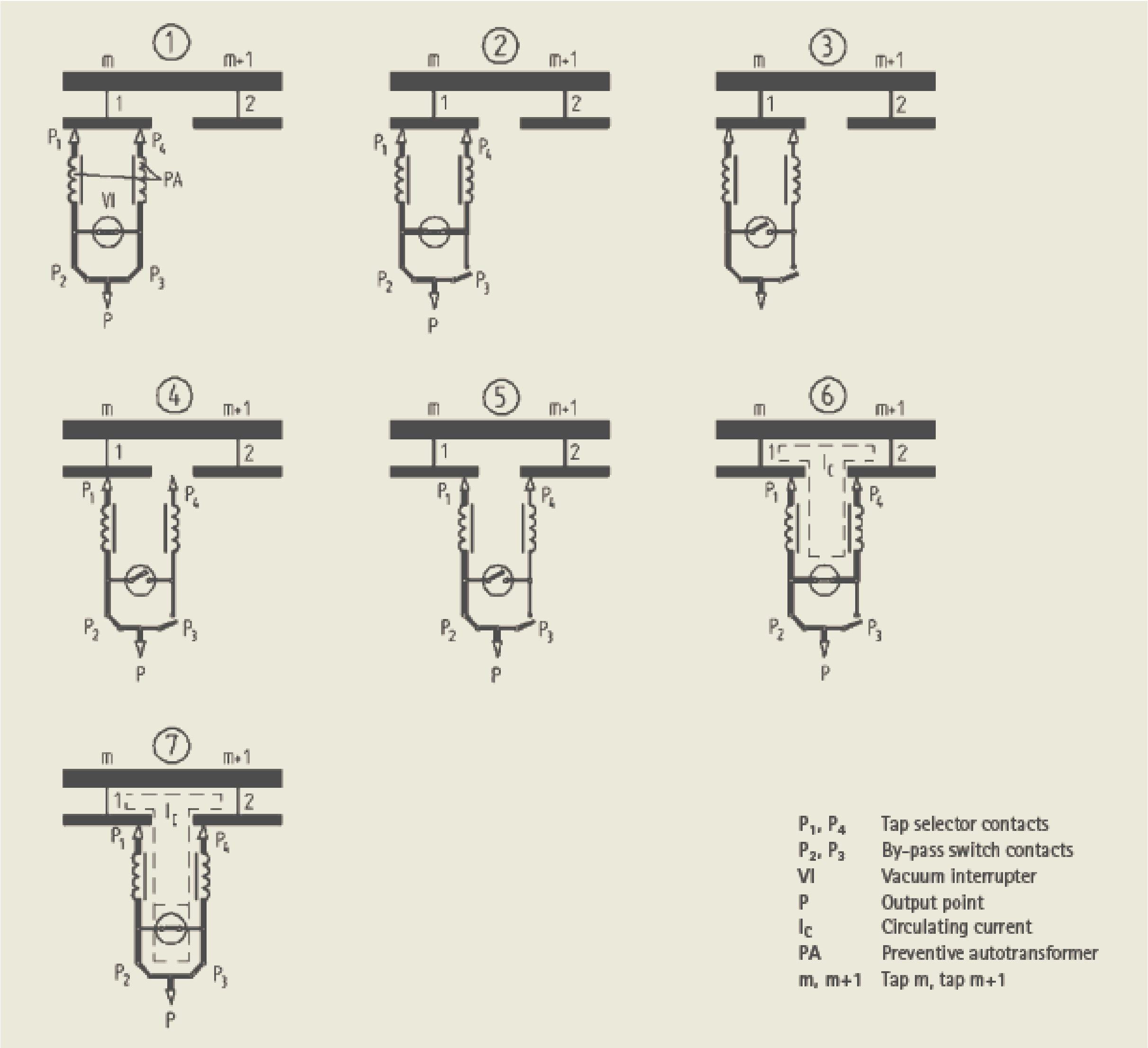

FIGURE 3.1-3 SWITCHING PRINCIPLE REACTANCE TYPE OLTC WITH VACUUM INTERRUPTER[54]

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[53] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013., chapter 4 page 18

[54] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013. , chapter 4 page 18

3.2 Regulation Types

It is possible to connect the tap winding with the other windings in different ways to reduce the needed turns of the tap winding or the number of switches.

Linear: Turns of the tap winding are added to the main winding and the voltage over the tap winding is added to the main voltage, no changeover switch is needed. Therefore minimum tap position represents only the main winding no parts of tap winding is inside the circuit.

Reverse: Turns of the tap winding can be added or subtract to the main windings. Changeover switch is needed but for the full regulation range only half of the windings in the tap winding are needed compared to linear type. At the minimum tap position the total tap winding is in the circuit which leads to the maximum copper losses. The tap winding is outside the circuit in the middle (neutral) position. The negative and positive positions have the same number of position therefore the total number of positions is twice the positive positions plus one for the neutral.

Coarse-fine: Is a two stage linear regulation method. The coarse stage consists of a large number of turns and has only one position. They can be completely inserted into the circuit or not. The fine stage consists of many position and the turns can be added to the main winding. The total number of positions is twice the number of positions of the fine winding plus one. An advantage of this type are the lower copper losses compared to the reverse type at the minimum tap position. Disadvantage can be that two separate tap windings are needed.

Bias winding: Is more or less the same as a coarse-fine regulation. The winding consists of one tap position with half the number of turns of the other main tap positions. This half step can be added or not to the other steps and allows half steps between the main steps. The total number of available positions is twice the number of the main tap positions plus one.[55]

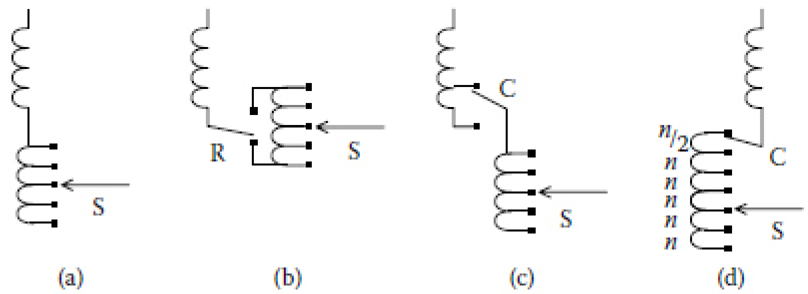

FIGURE 3.2-1 DIFFERENT REGULATION TYPES[56]

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[55] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, chapter 16 page 550-551

[56] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, chapter 16 page 551

Another possibility to regulate the voltage without a separate regulation winding is to place the regulation taps on one of the main windings which is called "tapped-winding". In the winding arrangement the tapped winding must be the outermost winding. A tapped winding has the advantage that no additional tap winding is needed. Nevertheless a disadvantage is that during the regulation process the winding height changes and this will produce additional forces. This regulation type will be discussed in chapter 5.

Independent of the different regulation types the electrical designer has the possibility to choose the place for the regulation winding on the transformer. The most common place for the tap winding is at the neutral end of a star-connected HV-winding because it allows to use a low voltage class three phase OLTC. With delta windings no neutral point exists for the tap winding. Electrical designers have the possibility to place the tap winding at line end or in the middle of the main winding. At line end the tap changer needs to be fully insulated from the system voltage. In the mid-position the dielectric stress is reduced but this place has more influence on the transformer impedance.[57]

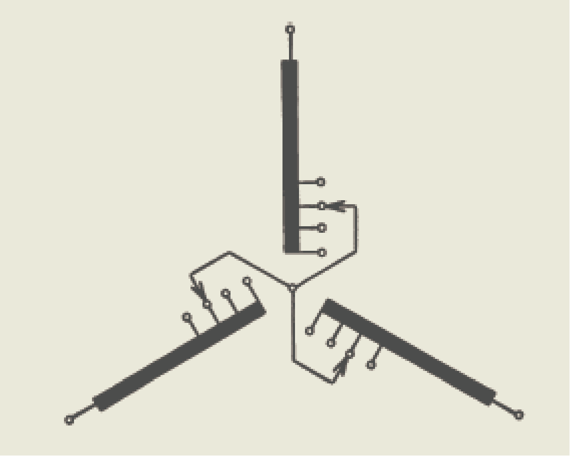
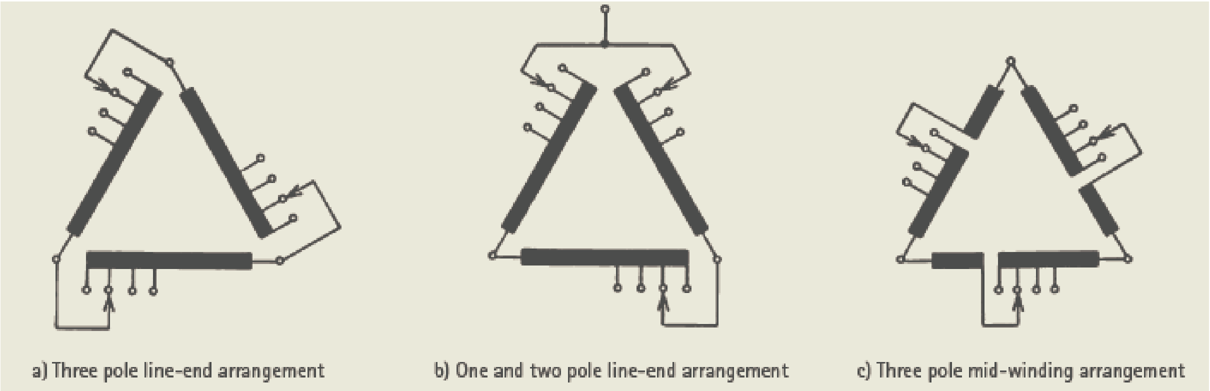


FIGURE 3.2-2 OLTC WITH NEUTRAL END OF TAP WINDING[58]



a) Three pole line-end arrangement

b) One and two pole line-end arrangement

c) Three pole mid-winding arrangement

FIGURE 3.2-3 OLTC WITH DELTA CONNECTION OF TAP WINDING[59]

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[57] R. Küchler, *Die Transformatoren.* 1956, chapter 7 page 201-203

[58] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013., chapter 3 page 5

[59] Dr. D. Dohnal, "On load tap changers for power transformers," *Maschinenfabrik Reinhausen GmbH,* 2013., chapter 3 page 5

3.3 Voltage regulation types

For a transformer there are two possible places to insert the tap winding. The place of the tap winding and the side for the regulation will decide which voltage regulation is used. Generally there are two types, one with constant flux this means that adding or subtract parts of the tap winding to the main winding will not affect the magnetic flux and keep them constant which means that the voltage per turn keeps constant. The other possibility is that the additional taps affect the magnetic flux and the flux will change for every tap positions and also the voltage per turn will change for every position.

Constant flux regulation:

Regulation with constant flux is made for example when the tap winding is inserted on the side of the regulation voltage. This implies that for primary side regulation the tap winding is placed on the primary side and vice versa for secondary side regulation on the secondary side. Regulation on the secondary side will lead to a high current over the tap winding and the switch and so it is possible that the switches are only single bank and not three bank switches and single bank are more expensive. Another disadvantage can be that normally the main secondary winding has not so many turns that it could be difficult to make a tap winding with the needed turns. Therefore it could be a better option for secondary side regulation to change to variable flux regulation.

Variable flux regulation:

Regulation with variable flux happens when the tap winding is not placed at the same side as the regulation voltage. For example for secondary side regulation the tap winding is placed on the primary side. Advantage for secondary side regulation can be that the current over the switch is not so big so three bank switch is possible, this will reduce the costs and it will be easier to create a tap winding because more turns are needed. Disadvantages are that the core must be designed for the maximum flux which happens at the minimum tap position and to avoid saturation of the core. Changes of flux will vary the no load losses because of their dependence on the flux. If the transformer has a tertiary winding additional inductors are necessary to keep the voltage over the winding constant and produces additional costs.

All the methods where the tap winding is on the transformer are called **direct regulation** and it makes no difference between constant- and variable flux regulation. If regulation on the LV-side is necessary but the current for a tap changer is too high there is the possibility to use an auxiliary transformer. This type of regulation where the regulation is made with an auxiliary transformer is called **indirect regulation** and is also independent of the type of flux regulation.

There are two possibilities of indirect regulation.

(a) shows a series voltage regulation where the main transformer can be designed independently from the auxiliary transformer because the tap winding is located on them and adds or subtract a voltage to the LV-side.

(b) shows a series (booster) transformer, here the tap winding is a separate winding on the main transformer. The electrical designer has more flexibility in the design of the tap winding and can limit the current over the tap changer.

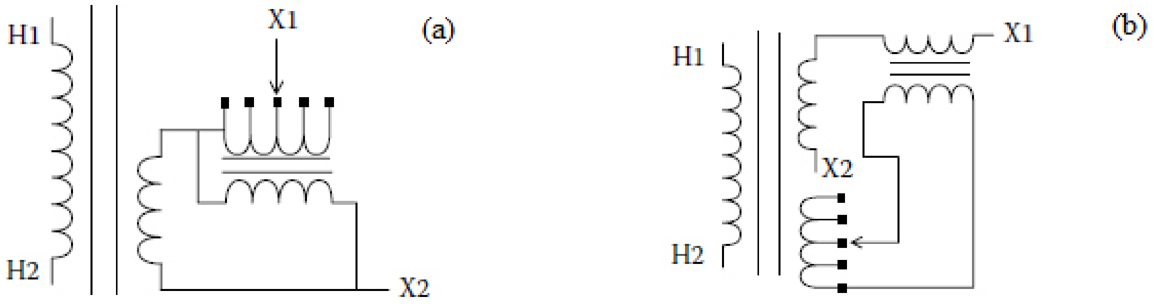

FIGURE 3.3-1 INDIRECT REGULATION SCHEMAS FOR TRANSFORMER[60]

4. Voltage regulation for autotransformer

For regulating an autotransformer there are not so many differences to a transformer. OLTCs and DETCs are the same. The regulation types are also the same and generally the voltage regulation types are the same but for an autotransformer the electrical designer has much more possibilities to place the tap winding to gain more advantages or disadvantages. These places will be shown now, divided by the regulation side.

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[60] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. M. Shah and R. Ahuja, *Transformer Design Principles.* New York: CRC Press, 2010, chapter 16 page 561

4.1 Voltage regulation types

First we take a look at circuits for regulation the HV-side and keeping the LV-side constant.

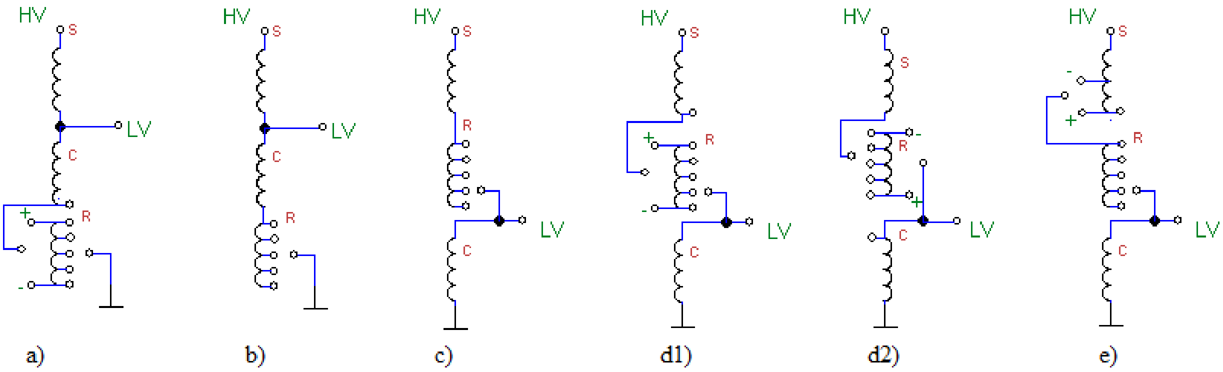

FIGURE 4.1-1 WINDING ARRANGEMENTS FOR REGULATING THE HIGH VOLTAGE

Arrangement (a) shows a reverse regulation type with variable flux where the tap winding is placed in the neutral end in series with the series and common winding. Therefore by adding or subtracting windings the voltage per turn and as explained in chapter 2 the magnetic flux must change to keep the LV-side constant. Advantage of this regulation is that by placing the tap winding in the neutral point the lowest insulation level is needed. Disadvantage is the variable flux which must take into account by designing the magnetic circuit and calculating the no load losses. (b) shows a linear regulation type with variable flux. The tap winding is placed in the neutral end and a disadvantage to (a) is that for the same regulation range compared to the reverse type more turns are needed. Arrangement (c) shows a linear regulation type with constant flux where the tap winding is placed in between the series and common winding. Advantage is that the magnetic flux is keeping constant this leads to constant no load losses over the full regulation range. Disadvantage compared to a reverse type is that the double amount of turns is needed for the same regulation range and compared to arrangement (a) a higher insulation will be needed. Arrangements (d1) and (d2) show a reverse regulation type with constant flux where the tap winding is placed in between series and common winding. Advantages are half of the number of turns from a linear type needed for the same regulation range. Constant flux regulation keeps the no load losses constant and the tap changer can be designed for a relative low current. The difference between (d1) and (d2) is the side of the diverter switch of the tap changer. In (d1) the voltage of the diverter switch is constant and is always the LV-side voltage. In (d2) the voltage varies with the tap position and could lead to higher cost for the insulation of the diverter switch because U_m changes. Disadvantage to (a) is the higher insulation level. (e) shows a coarse/fine regulation type with constant flux[61]

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[61] A. Krämer, *On-Load Tap-Changers for Power Transformers.* Spintler - Medienhaus Weiden, 2000, chapter 3 page 67

Now we will regulate LV-side and keep the HV-side constant.

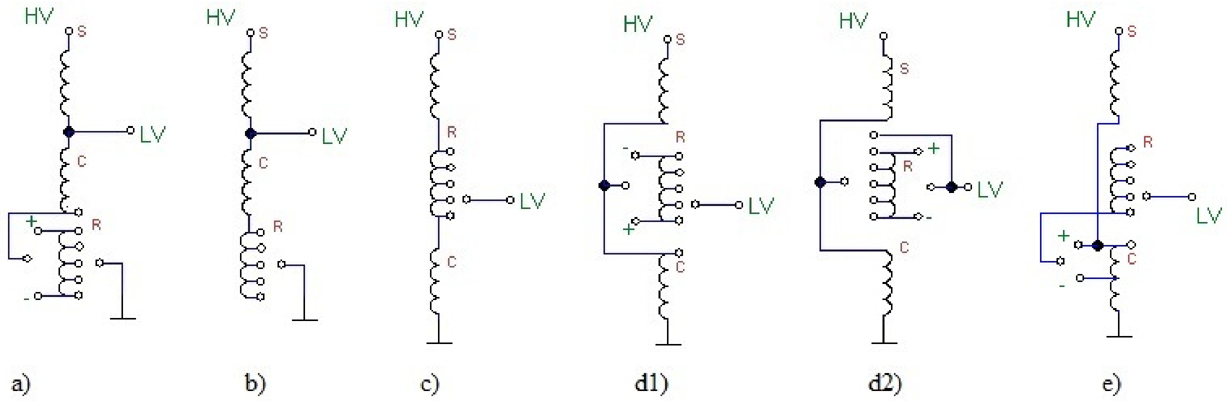

FIGURE 4.1-2 WINDING ARRANGEMENT FOR REGULATING THE LOW VOLTAGE

Arrangement (a) can be used for regulating the HV-side as explained above or now for regulating the LV-side. It stays a regulation with variable flux because now the HV-side should keep constant while the LV-side changes. The advantages and disadvantages will be the same compared to regulating the HV-side. (b) shows a linear regulation type with variable flux. The tap winding is placed in the neutral end and a disadvantage to (a) is that for the same regulation range compared to the reverse type more turns are needed. Arrangement (c) shows a linear regulation type with constant flux where the tap winding is placed in between the series and common winding. Advantage is that the magnetic flux is keeping constant this leads to constant no load losses over the full regulation range. Disadvantage compared to a reverse type is that the double amount of turns is needed for the same regulation range. Arrangements (d1) and (d2) show a reverse regulation type with constant flux where the tap winding is placed in the LV-line. Advantages are half of the number of turns from a linear type needed for the same regulation range. Constant flux regulation keeps the no load losses constant and the tap changer can be designed for a relative low current. The difference between (d1) and (d2) is the side of the diverter switch of the tap changer. In (d2) the voltage of the diverter switch is constant and is always the voltage over the common winding. In (d1) the voltage varies with the tap position and could lead to higher cost for the insulation of the diverter switch because U_m changes. Disadvantage to (d) is the higher insulation level. (e) shows a coarse/fine regulation type with constant flux.[62]

Generally for regulation with variable flux in combination with a tertiary winding, there are also additional inductors needed to keep the voltage over the tertiary winding constant.

For a linear or reverse regulation type with constant flux the needed turns of the different windings for a given regulation range can be calculated with the standard transformer equation for a given voltage per turn, HV- and LV-voltage and the regulation range. For calculating the needed turns of the series- common- and tap winding for regulation with

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[62] A. Krämer, *On-Load Tap-Changers for Power Transformers.* Spintler - Medienhaus Weiden, 2000, chapter 3 page 65-66

variable flux other equations are needed. Therefore the needed turns will be calculated in a simple example.

For an autotransformer with 400kV/220kV +-15% and a voltage per turn VpT=258V with regulation arrangement (a) of figure 4.1-2 the turns for the different windings will be.

$$V_+ = \frac{V_{1+}}{V_{2-}} \qquad V_- = \frac{V_{1-}}{V_{2+}}$$

$$n_s = \frac{V_- - 1}{V_-} \qquad n_c = \frac{V_+ + V_- - 2}{2 \cdot V_- \cdot (V_+ - 1)} \qquad n_r = \frac{V_+ - V_-}{2 \cdot V_- \cdot (V_+ - 1)}$$

$$N_s = n_s \cdot ratio \qquad N_c = n_c \cdot ratio \qquad N_r = n_r \cdot ratio$$

V_{1+} … maximum voltage of HV-side
V_{1-} … minimum voltage of HV-side
V_{2+} … maximum voltage of LV-side
V_{2-} … minimum voltage of HV-side
N_s … Turns of series winding
N_c … Turns of common winding
N_r … Turns of tap winding

With the given values of the autotransformer we get

$$V_+ = \frac{400kV}{187kV} = 2.14 \qquad V_- = \frac{400kV}{253kV} = 1.58$$

$$n_s = \frac{V_- - 1}{V_-} = 0.367 \qquad n_c = \frac{V_+ + V_- - 2}{2 \cdot V_- \cdot (V_+ - 1)} = 0.478$$

$$n_r = \frac{V_+ - V_-}{2 \cdot V_- \cdot (V_+ - 1)} = 0.155$$

To get the value of the ratio we need the turns of one winding. With the given VpT the turns for the series winding can be calculated.

$$N_s = \frac{\frac{V_1 - V_2}{\sqrt{3}}}{VpT} = \frac{\frac{400kV - 220kV}{\sqrt{3}}}{258V} = 403$$

$$ratio = \frac{N_s}{n_s} = \frac{403}{0.367} = 1098$$

With the value for the ratio the turns for the common- and tap winding can be calculated and we get N_c=525 and N_r=170

Over the regulation range for every tap position a different number of turns of the tap winding must be added or subtract to the total number of turns.

All this possible voltage regulation types are **direct regulation methods** because as mentioned in chapter 3.3 the tap winding is on the autotransformer. But for the same reasons as for the transformer it is also possible to use **indirect regulation methods** for autotransformers. The definition and principles of them keeps the same as in 3.3.

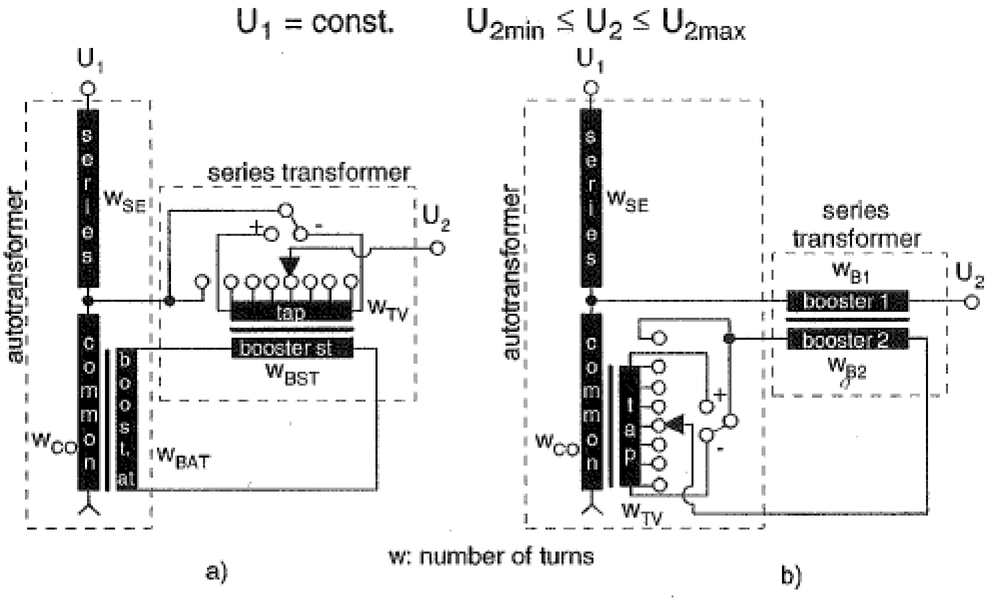

FIGURE 4.1-3 INDIRECT REGULATION METHODS FOR AUTOTRANSFORMERS[63]

5. Short circuit impedance calculation

In chapter two it was mentioned that no ideal transformer exists. This means that not all of the magnetic flux is linked with the iron core. The flux, which does not flow in the core is called leakage flux. The leakage flux under no-load is very small but under load condition it produces a leakage flux for the short circuit impedance. In a real transformer the leakage flux is represented with the leakage reactance in the equivalent circuit. During a short circuit, the equivalent circuit of the transformer of chapter two changes to the following circuit.

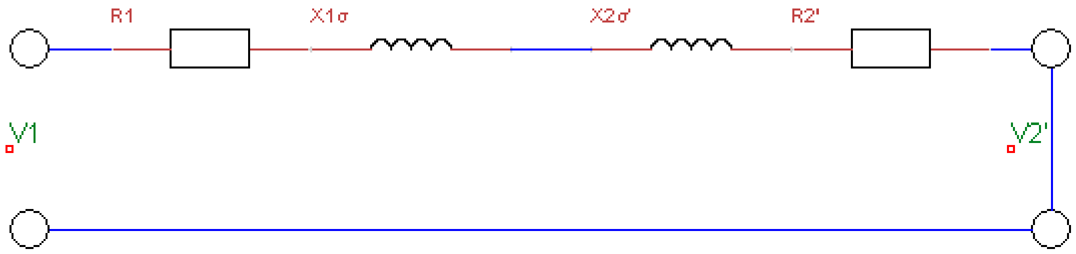

FIGURE 5-1 EQUIVALENT CIRCUIT OF A TRANSFORMER UNDER SHORT CIRCUIT CONDITIONS

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[63] A. Krämer, *On-Load Tap-Changers for Power Transformers.* Spintler - Medienhaus Weiden, 2000, chapter 3 page 70

The resistances and the leakage reactances are represented the short circuit impedance Z, which will be.

$$R = R_1 + R_2' \qquad\qquad X = X_{1\sigma} + X_{2\sigma}'$$

$$Z = \sqrt{R^2 + X^2}$$

Usually the resistances are very small so that for general talking about the short circuit impedance, the resistances can be ignored. Therefore to calculate the impedance only the leakage reactance needs to be calculated.

To calculate the leakage reactance first we have to calculate the leakage flux. For calculating them the winding arrangement should full fill the following conditions:

1. The sides of the windings with exception facing the stray gap surrounded by iron with infinitely high permeability.

2. The winding cross sections are completely flooded with current.

3. The reaction of the current displacement in the conductors on the leakage flux is neglectable.

Condition three is fulfilled with transposing the conductors and splitting them into many strips. It is also fulfilled for flat conductors because they have a large surface area and a small thickness compared to other conductors to reduce the effects of the skin effect too. Number two has to be fulfilled because areas with current density zero inside the windings must be avoid for the calculation of the magnetic induction. Especially for areas with cooling ducts or insulation layers parallel to the stray gap this condition is not fulfilled. They will lead to a subdivided winding but we will see later that the leakage reactance for subdivided windings can be calculated too. Number one is not really fulfilled because not all sides of the windings are surrounded by the core. For different winding heights the axial and radial components of the leakage flux change which will affect the value of the leakage reactance. Therefore Rogowski inserted a correction factor for taking this into account.[64]

Let's start with the calculation for concentric primary and secondary windings. The windings will have the same height and a uniform ampere turn distribution. This leads to a leakage flux only in axial direction. The winding arrangement will be the following.

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[64] R. Küchler, *Die Transformatoren.* 1956, chapter 2 page 58-60

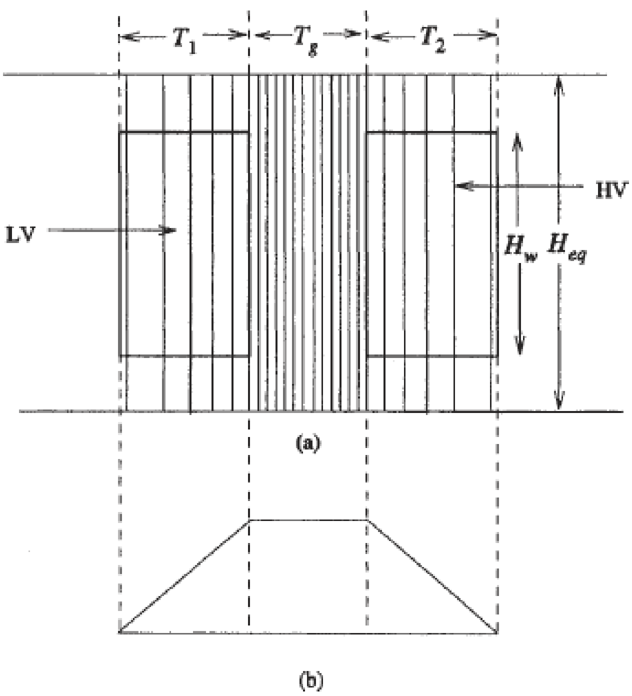

FIGURE 5-2 LEAKAGE FIELD WITH EQUIVALENT HEIGHT (A) AND MAGNETOMOTIVE FORCE (MMF) OR FLUX DENSITY DIAGRAM (B)[65]

The winding height H_w is divided by the rogowski factor K_R to get the equivalent height H_{eq} for the calculation. The height is given in centimetres.

$$H_{eq} = \frac{H_W}{K_R}$$

K_R is given by

$$K_R = 1 - \frac{1 - e^{\frac{-\pi \cdot H_W}{T_1 + T_g + T_2}}}{\frac{\pi \cdot H_W}{T_1 + T_g + T_2}}$$

The mmf for a point depends on the ampere turns enclosed at this point. Inside the LV winding it increases from zero to the maximum value. In the gap between LV and HV it stays constant and inside the HV it decreases from the maximum to zero again.

The general formulation for the flux linkage of a flux tube like in figure 5.2 is

$$B_x = \frac{\mu_0 \cdot (N \cdot I)_x}{H_{eq}} \qquad [Gauss]$$

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[65] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 3 page 79

Now the r.m.s value of the flux linkage at any distance x from the inner diameter ID will be

$$B_x = \frac{\mu_0}{H_{eq}} \cdot \left[\left(a + \frac{b-a}{R} \cdot x\right) \cdot NI\right]$$

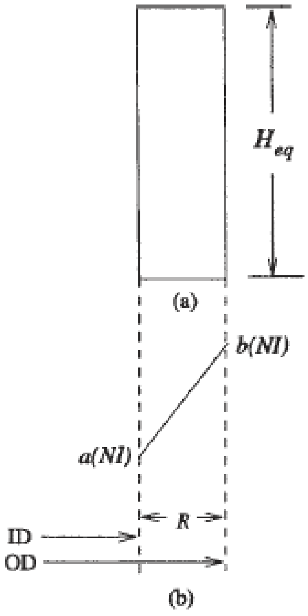

FIGURE 5-3 (A) FLUX TUBE (B) MMF DIAGRAM[66]

Now there are two different ways to calculate the reactance. One is based on the fundamental definition of inductance

$$L = \frac{N \cdot B \cdot A}{I}$$

The second one is over the connection of the magnetic energy and the inductance.

$$L = \frac{2 \cdot W_m}{I^2}$$

Both will lead to the same result and here we will take the way over the magnetic energy.

Energy per unit volume in the magnetic field in air with linear magnetic characteristics will be

$$w = \frac{B^2}{2\mu_0}$$

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[66] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 3 page 80

The differential energy dW_x for a cylindrical ring of height H_{eq} with thickness dx and diameter (ID+2x) is

$$dW_x = \frac{B_x^2}{2\mu_0} \cdot (volume\ of\ cylindrical\, ring) = \frac{B_x^2}{2\mu_0} \cdot \pi \cdot (ID + 2x) \cdot H_{eq} dx$$

Now we can substitute B_x with the equation from above for the simple flux tube in (figure 5.2) with conditions a=0 and b=1 and we get

$$dW_x = \frac{\mu_0 \pi (NI)^2 x^2 (ID + 2x)}{2R^2 H_{eq}} dx$$

For the winding arrangement in (figure 5.1) the total energy stored in the LV winding by replacing R with T_1 will be

$$W_1 = \frac{\mu_0 \pi (NI)^2}{2T_1^2 H_{eq}} \int_0^{T_1} x^2 (ID + 2x) dx = \frac{\mu_0 \pi (NI)^2}{2H_{eq}} \frac{1}{3} \left\{ ID + \frac{3T_1}{2} \right\} T_1$$

The term in the brackets can be approximated as mean diameter D_1 of the LV-winding

$$W_1 = \frac{\mu_0 \pi (NI)^2}{2H_{eq}} \frac{1}{3} D_1 T_1$$

The energy in the HV-winding is similar

$$W_2 = \frac{\mu_0 \pi (NI)^2}{2H_{eq}} \frac{1}{3} D_2 T_2$$

In the gap between the windings the flux density is constant therefore the energy there will be

$$W_g = \frac{B_g^2}{2\mu_0} \cdot (volume\ of\ cylindrical\ gap) = \frac{1}{2\mu_0} \cdot \left[\frac{\mu_0 (NI)}{H_{eq}} \right]^2 \pi \cdot D_g \cdot T_g \cdot H_{eq} dx$$

With the sum of the energies we get for the inductance

$$L = \frac{2 \cdot (W_1 + W_g + W_2)}{I^2} = \frac{\mu_0 \pi N^2}{H_{eq}} \left[\frac{1}{3} (T_1 D_1 + T_2 D_2) + T_g D_g \right]$$

And the leakage reactance will be

$$X = 2\pi f L = 2\pi f \frac{\mu_0 \pi N^2}{H_{eq}} \left[\frac{1}{3} (T_1 D_1 + T_2 D_2) + T_g D_g \right]$$

The percent leakage reactance and by definition the short circuit impedance will be

$$u_k = \%X = \frac{X}{Z_b} = \frac{I \cdot X}{V} \cdot 100 = 2\pi f \frac{\mu_0 \pi I N^2}{H_{eq} V} \left[\frac{1}{3}(T_1 D_1 + T_2 D_2) + T_g D_g\right] \cdot 100$$

$$= 2\pi f \frac{\mu_0 \pi I N}{H_{eq} \frac{V}{N}} \left[\frac{1}{3}(T_1 D_1 + T_2 D_2) + T_g D_g\right] \cdot 100$$

V is the rated voltage V/N will be the voltage per turn VpT and by inserting everything in cm and not in mm and for a frequency of 50Hz the formula can be simplified to[67]

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq} \frac{V}{N}} \left[\frac{1}{3}(T_1 D_1 + T_2 D_2) + T_g D_g\right]$$

To simplify the formula D_1 , D_2 and D_g are replaced by the mean diameter of the winding arrangement D_m and therefore the formula looks like that

$$D_m = \frac{D_1 + D_2 + D_g}{3}$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq} \frac{V}{N}} \left[\frac{1}{3}(T_1 + T_2) + T_g\right] \cdot D_m$$

For windings where the LV- and HV-windings are inserted like a sandwich (figure 5.3) the same reactance formulas can be used but they need a little modification for that arrangement

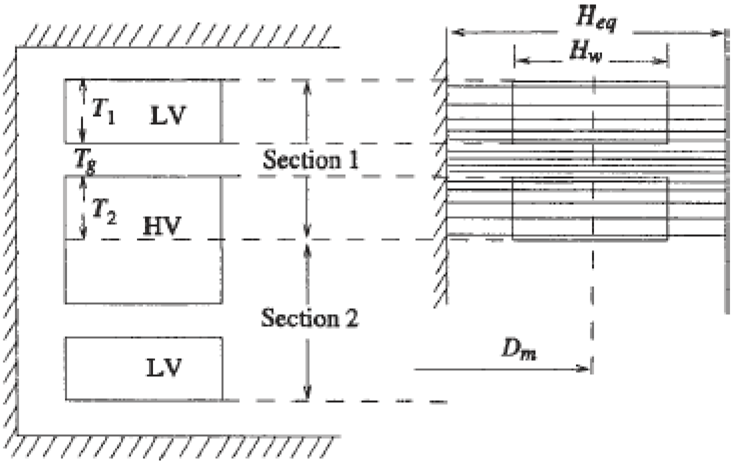

FIGURE 5-4 SANDWICH WINDING[68]

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[67] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 3 page 79-82

[68] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 3 page 83

If the sections connected in series the reactance will be

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \cdot \frac{1}{S} \cdot \left[\frac{1}{3}(T_1 D_m + T_2 D_m) + T_g D_m\right]$$

With S is the number of sections.

If the windings are not from the same height or they have a non-uniform ampere turn distribution the leakage flux consists of an axial part and a radial part. Normally the electrical designers try to build the windings with the same height to reduce the short circuit forces on the windings. Nevertheless when the tappings placed on a main winding instead of a separate winding for every tap position the ampere turn distribution changes. To reduce the radial flux the taps are placed symmetrically in the middle or at the ends of the winding. The winding arrangement and the mmf diagram are presented in figure 5.4. To calculate the reactance, the actual configuration is split into the axial and radial part of the flux. The effect of the gap in winding two can be taken into account by replacing winding two with winding three and four. Winding three has the same ampere turn distribution as number one now it is possible to calculate the reactance for axial part with the formula for concentric windings which is explained above. Winding four must have an ampere turn distribution that the addition of three and four along the height will lead to the ampere turn distribution of two. The reactance for the radial part must be calculated with winding four by taking four as a sandwich winding and the sections connected in series. The total reactance will be the sum of the axial and radial part therefore it is clear that a non-uniform ampere turn distribution will produce a higher leakage reactance.

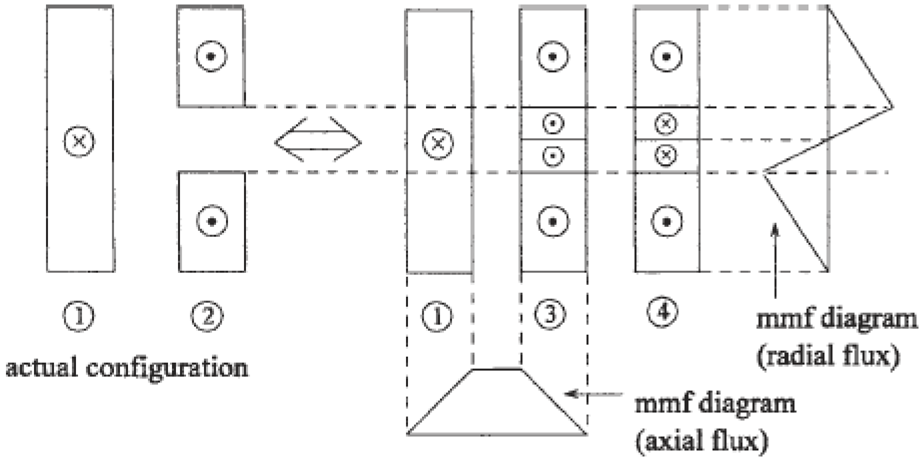

FIGURE 5-5 WINDING ARRANGEMENT[69]

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[69] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design and Practice.* Marcel Dekker Inc., 2004, chapter 3 page 84

If there are more than two windings or one winding is divided by a gap which will have the same affect the arrangement not only consists of main leakage gap there are one or more auxiliary gaps too. All windings will have the same height so that only an axial leakage flux consists for the calculation. Therefore the reactance calculation becomes more complex. The basic principles therefore have been made by Werner Knaack in “Berechnung der Streuspannung bei doppelkonzentrischer Wicklungsanordnung”[70] and by Werner Knaack and Hans Schwaab in “Zusätzliche Streuung bei Transformatoren”[71] and they are still valid.

These principles are also based on the magnetic energy. For a concentric winding arrangement with one subdivided winding and the ampere-turn diagram (figure 5-6) the following calculation steps must be done.

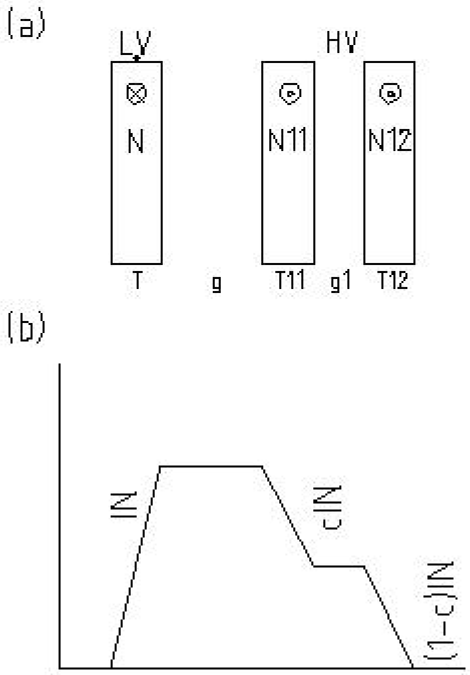

FIGURE 5-6 SUBDIVIDED WINDING (A) AND AMPERE-TURN DIAGRAM (B)

First c the ratio of the ampere turns of the first part of the subdivided winding to the total ampere turns must be calculated.

$$c = \frac{I_1 N_{11}}{I_1 N_{11} + I_1 N_{12}} \qquad I_1 N_{11} + I_1 N_{12} = IN$$

Generally it can be written

$$I_1 N_{11} = cIN \qquad I_1 N_{12} = (1 - c)IN$$

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[70] W. Knaack, "Berechnung der Streuspannung bei doppelkonzentrischer Wicklungsanordnung," *Archiv Für Elektrotechnik,* vol. 34, pp. 358-362, 1940.

[71] W. Knaack and H. Schwaab, "Zusätzliche Streuung bei Transformatoren," *Archiv Für Elektrotechnik,* vol. 32, pp. 470-482, 1938.

Then the magnetic energy for each part must be calculated. For the energy in the LV-winding we get

$$W_1 = \frac{\mu_0 \pi (NI)^2}{2H_{eq}} \frac{1}{3} D_1 T$$

The energy in the gap between LV and the first part of the HV-winding is

$$W_2 = \frac{\mu_0 \pi (NI)^2}{2H_{eq}} D_g g$$

For the first part of the HV-winding two terms for the energy must be calculated. One for the decreasing ampere-turns cIN in the winding and one for the ampere-turns which are still present (1-c)IN

For the decreasing ampere turns the energy will be

$$W_3 = \frac{\mu_0 \pi (cNI)^2}{2H_{eq}} \frac{1}{3} D_{11} T_{11}$$

And for the other ones

$$W_4 = \frac{\mu_0 \pi ((1-c)NI)^2}{2H_{eq}} D_{11} T_{11}$$

The energy in the auxiliary gap is

$$W_5 = \frac{\mu_0 \pi ((1-c)NI)^2}{2H_{eq}} D_{g1} g_1$$

At least the energy in the second part of the HV-winding is

$$W_6 = \frac{\mu_0 \pi ((1-c)NI)^2}{2H_{eq}} \frac{1}{3} D_{12} T_{12}$$

With the sum of the energies the reactance will be

$$X = 2\pi f \cdot \frac{2 \cdot (W_1 + W_g + W_2)}{I^2}$$

With some simplifications the formula for the percentage leakage reactance looks like

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq} \frac{V}{N}} \delta' \cdot D_m$$

The reduced air gap δ' is

$$\delta' = \frac{T}{3} + g + \alpha \cdot T_{11} + \beta \cdot (g_1 + \frac{T_{12}}{3})$$

With

$$\alpha = 1 - c + \frac{c^2}{3} \qquad\qquad \beta = (1-c)^2$$

And the mean diameter D_m will be

$$D_m = d_1 - \frac{2}{3}T + \delta'$$

With d_1 is the outer diameter of the inner winding.

The value of c shows the winding arrangement for example:

$c < 1$ for a subdivided concentric arrangement as shown above

$c = 1$ for a concentric arrangement

$c > 1$ for a double-concentric arrangement when the value of one ampere-turn part becomes negative

The formulas for a subdivided concentric and concentric arrangement are given but there are two possible circuits for a double-concentric arrangement.

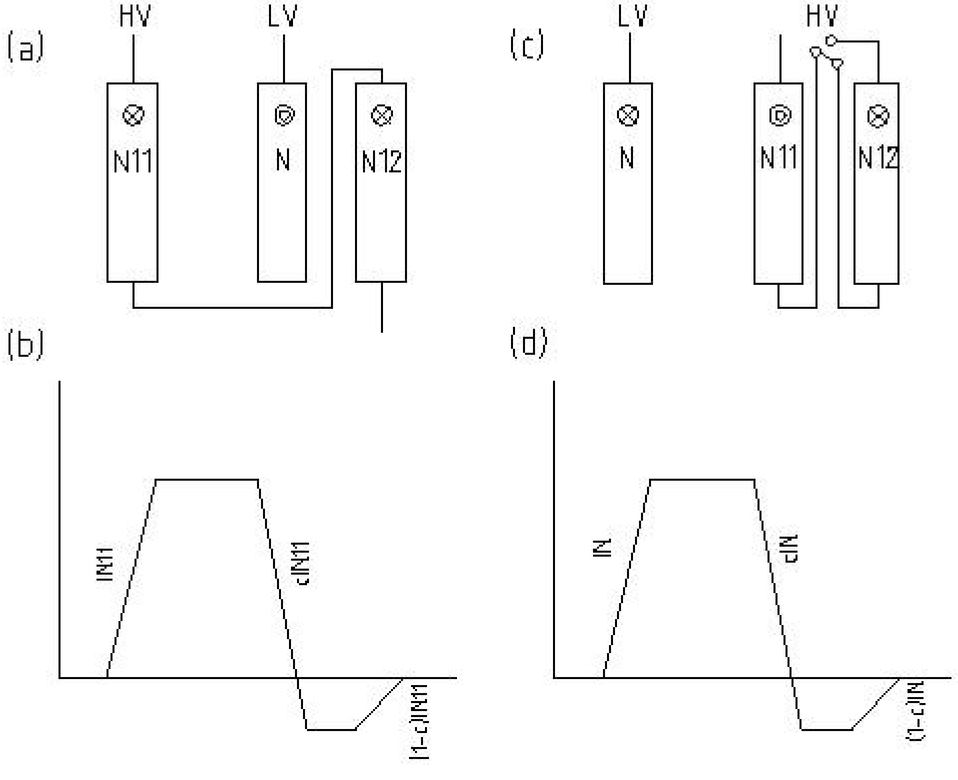


FIGURE 5-7 DIRECT DOUBLE-CONCENTRIC CIRCUIT (A) AND AMPERE-TURN DIAGRAM (B) INDIRECT DOUBLE-CONCENTRIC CIRCUIT (C) AND AMPERE-TURN DIAGRAM (D)

For an indirect double-concentric arrangement the formula is the same as for the subdivided concentric arrangement. However for direct double-double concentric arrangement the factor

$$\frac{1}{c^2}$$

must be added because the initial ampere turns at the left side are not IN now they are IN_{11} but for calculating the energies again with IN the factor needs to be added and the new formula will be

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \delta' \cdot D_m \cdot \frac{1}{c^2}$$

Finally these are the formulas for a transformer for these types of winding arrangements where all windings will have the same height.

Winding arrangement	formula
Subdivided concentric	$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \delta' \cdot D_m$
Concentric	$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \left[\frac{1}{3}(T_1 + T_2) + T_g\right] \cdot D_m$
Direct double concentric	$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \delta' \cdot D_m \cdot \frac{1}{c^2}$
Indirect double-concentric	$u_k = 1.25 \cdot 10^{-3} \cdot \frac{IN}{H_{eq}\frac{V}{N}} \delta' \cdot D_m$

With these formulas it is visible how we can change the short circuit impedance. It mainly depends on geometric parameters of the winding arrangement. For a low value it is better to design a winding where the ratio between height and width is high because so the u_k will be low. Nevertheless the maximum height of the winding is limited by factory and transportation limits. Another possibility for a low value is to reduce the insulation thickness by using a barrier insulation system. It looks like that reducing the number of turns could reduce u_k but as explained in chapter 2 this will increase the flux results in higher core losses or it will increase the core diameter and this will increase the mean diameter and it will neglect the effects of a lower number of turns.

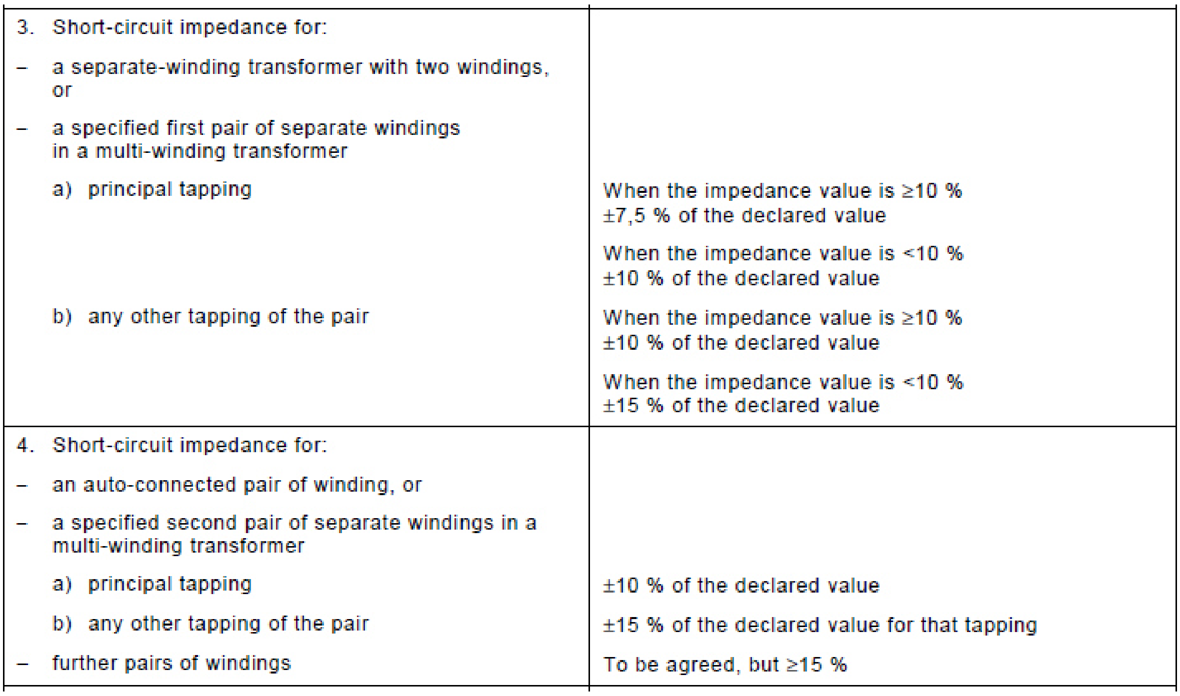
For the short circuit impedance uk_{AT} of an autotransformer the same formulas are valid too but an extra factor needs to be added to all the formulas to take the special connection of the windings and the fact that not all of the power is transferred via induction from one side to the other. In chapter 2.1 this fact was explained and the factor was introduced and we get

$$uk_{AT} = u_k \cdot \frac{1}{F_C}$$

If the transformer or autotransformer has an additional tertiary winding, the place of them in the winding arrangement could affect the short circuit impedance between the LV-winding and HV-winding. If the tertiary is the nearest winding to the core the mean diameter of the formulas for the calculations increases and therefore the value of u_k increases. An advantage of this position could be that it allows the HV-winding to have centre exits. If the tertiary is the outside winding it will not affect the mean diameter and so it does not affect u_k but a disadvantage could be that the HV-winding has no centre exits.

As explained in chapter 3 it is possible to use a tapped winding instead of an extra regulation winding for the regulation. A tapped winding has the advantage that there are only two windings needed for the regulation. Nevertheless during the regulation the height of the winding changes because the height depends on the tap position. Therefore we get an unsymmetrical mmf which means that there is an axial and radial component and for the calculation the radial component must be taken into account. The different heights combined with short circuit forces could also lead to some problems. If the winding and it is not important if concentric or double-concentric arrangement is subdivided into more parts the steps for the calculation will stay the same!

In real the height of the LV and HV winding are not equal. They vary in some centimetres but compared to the total height, which is normally more than two metres or is limited by transportation or factory limits, this are very small values. The fact that the value of u_k must be in a tolerance which are given below it was decided for the calculations to take the same height for all windings in the winding arrangement if there is no tapped winding. When we have a tapped winding the axial and radial components must be calculated.



3. Short-circuit impedance for:	
– a separate-winding transformer with two windings, or	
– a specified first pair of separate windings in a multi-winding transformer	
a) principal tapping	When the impedance value is ≥10 % ±7,5 % of the declared value When the impedance value is <10 % ±10 % of the declared value
b) any other tapping of the pair	When the impedance value is ≥10 % ±10 % of the declared value When the impedance value is <10 % ±15 % of the declared value
4. Short-circuit impedance for:	
– an auto-connected pair of winding, or	
– a specified second pair of separate windings in a multi-winding transformer	
a) principal tapping	±10 % of the declared value
b) any other tapping of the pair	±15 % of the declared value for that tapping
– further pairs of windings	To be agreed, but ≥15 %

Figure 5-8 Allowed Tolerances for the short circuit impedance (IEC 60076 part 1)[72]

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[72] "Power Transformer Part 1: General," *IEC 60076-1:2000 Edition 2. 1 2000-04,* 2000.

For regulation with a separate regulation winding it is allowed to say that the regulation winding has always the same height independent of the tap position. This is the fact because the regulation winding is designed as multiplex- or multilayer winding and therefore the winding does not change the height and the winding is tapped at the ends. Therefore no radial components need to be calculated.

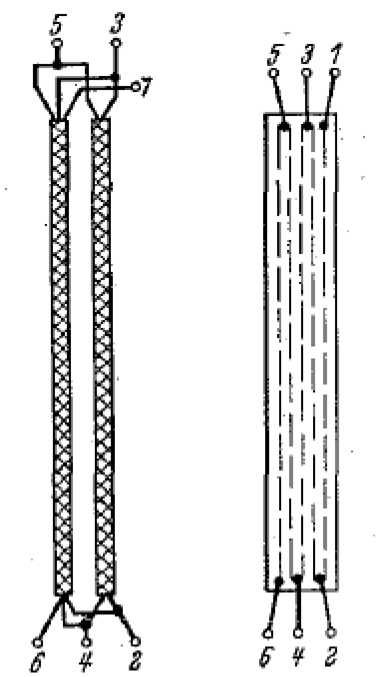

FIGURE 5-9 MULTIPLEX- OR MULTILAYER REGULATION WINDING[73]

These are the methods and formulas for the analytical calculation of the reactance, it can be calculated with numerical methods like FEM. For the preselection of the winding arrangement depending on the u_k it is enough to calculate them with the analytical methods. For an accurate value of u_k numerical methods are used because they do not use all the simplifications but numerical methods are more time expensive than the other one.

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[73] R. Küchler, *Die Transformatoren.* 1956, chapter 7 page 204

6. Results

Now with the given formulas the trend of the short circuit impedance for different autotransformer configurations should be calculated. The trend shows the change of u_k along the regulation range based on the value of u_k for the nominal tap position (0%).

First it is necessary to define the voltage levels for the primary and secondary side and the power level. By definition the voltage over the common and series winding is the primary side voltage, short **HV**, and the voltage only over the common winding will be the secondary side voltage, short **LV**.

These are:

voltage levels		power level
primary side	secondary side	
400kV	220kV	400MVA
400kV	135kV	400MVA
230kV	135kV	400MVA

TABLE 5 VOLTAGE LEVELS AND OUTPUT POWER

The next step is to specify the autotransformer configurations for the calculations. These are the regulation side, regulation type, voltage regulation type, winding arrangement and the regulation range.

The regulation side can be the primary side (HV) or the secondary side (LV).
From the possible regulation types explained in chapter 3 it was defined to use the reverse and the linear regulation type.
The voltage regulation can be done with constant flux or variable flux.
For the winding arrangement it was defined that the autotransformer has a tertiary winding too.
The autotransformer has the following windings:

tertiary winding	…	T
common winding	…	C
series winding	…	S
regulation winding	…	R

For example the winding arrangement looks like “TCSR”. This means that the innermost winding is the tertiary- and the outermost winding will be the regulation-winding.

Generally the regulation range for the reverse regulation type goes from -15% to +15% and for the linear regulation type from -5% to +5%. Values for the short circuit impedance calculated over the full regulation range for every 2.5% and the trend of them is presented in a graph.

Regulation side	Regulation type	Voltage regulation type	Winding arrangement
HV	reverse	constant flux	TCSR
HV	reverse	constant flux	TRCS
HV	reverse	constant flux	TCRS
HV	linear	constant flux	TCSR
HV	linear	constant flux	TRCS
HV	linear	constant flux	TCRS
HV	reverse	variable flux	TCSR
HV	reverse	variable flux	TRCS
HV	reverse	variable flux	TCRS
HV	linear	variable flux	TCSR
HV	linear	variable flux	TRCS
HV	linear	variable flux	TCRS
LV	reverse	constant flux	TCSR
LV	reverse	constant flux	TRCS
LV	reverse	constant flux	TCRS
LV	linear	constant flux	TCSR
LV	linear	constant flux	TRCS
LV	linear	constant flux	TCRS
LV	reverse	variable flux	TCSR
LV	reverse	variable flux	TRCS
LV	reverse	variable flux	TCRS
LV	linear	variable flux	TCSR
LV	linear	variable flux	TRCS
LV	linear	variable flux	TCRS
HV	tapped	constant flux	TCS

TABLE 6 SPECIFIED REGULATION CIRCUITS

The results for every configuration presented on the following pages and every configuration gets an own page. The page shows the regulation type, the winding arrangement with the theoretical ampere turn diagrams for the nominal tap position (0%) and the maximum tap positions (+15/5% and -15/5%) and the trend of the short circuit impedance. Additionally a table under the ampere turn diagrams is inserted and shows the change of the short circuit impedance for a variation of the insulation gap between two windings.

Another possible winding arrangement could be “TSCR” which is sometimes used but the trends of u_k compared to “TRCS” will only have little differences. “TSCR” is the result when “RCS” is vertically mirrored on the tertiary winding. So the trend will be the same only the values of u_k will vary because the geometry distances between the windings and the core changes. This is shown on the following example.

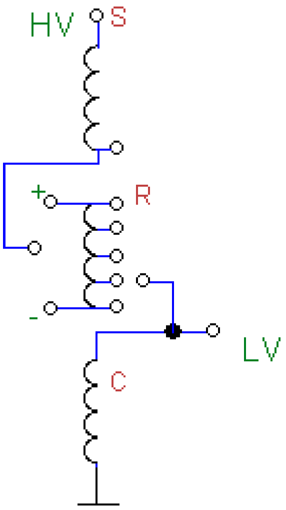


FIGURE 6-1HV-REVERSE REGULATION TYPE WITH CONSTANT FLUX

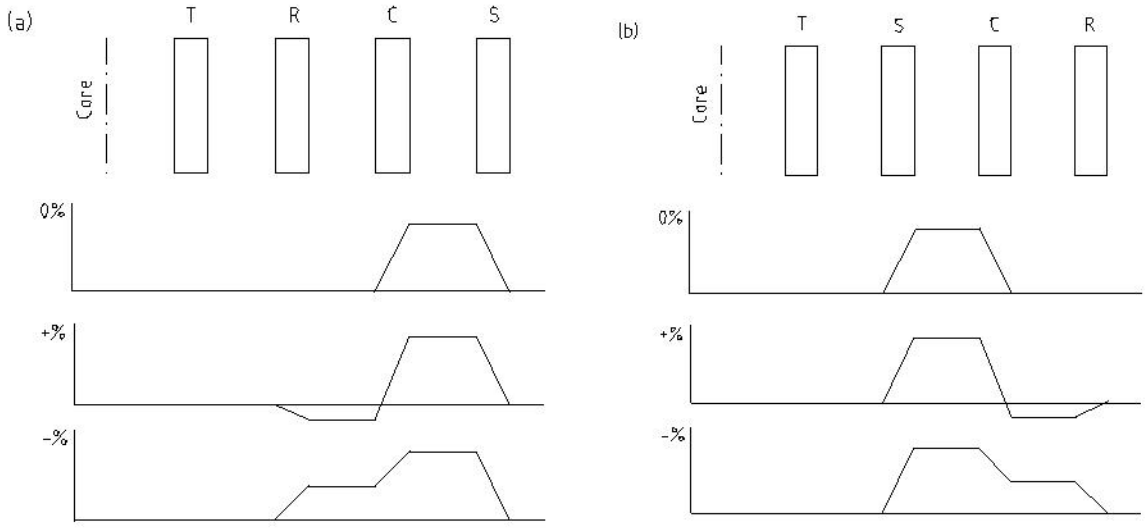


FIGURE 6-2 WINDING ARRANGEMENT AND AMPERE TURN DIAGRAMS FOR ARRANGEMENT (A) TRCS AND (B) TSCR

The calculations have been done with MATLAB and to show the steps during the calculations two examples will be shown here.

The first example is an Autotransformer with HV-regulation with constant flux and reverse regulation type and the following winding arrangement.

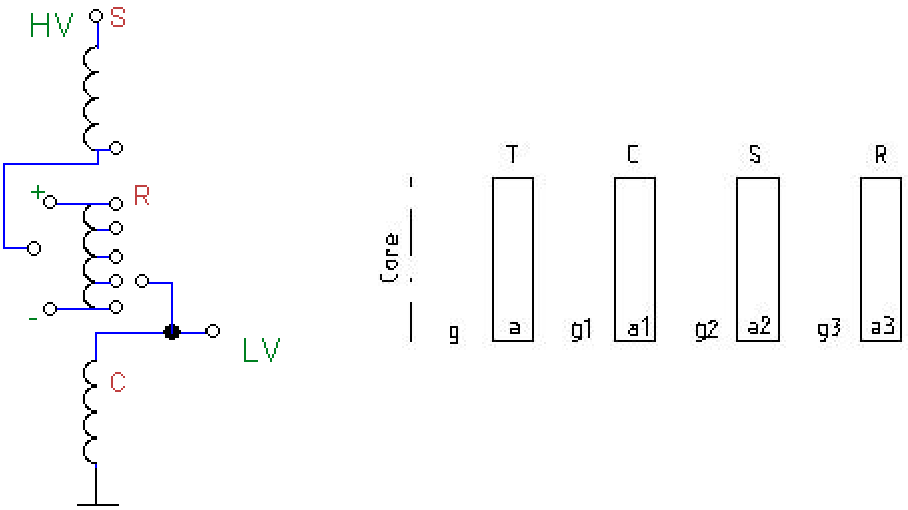


FIGURE 6-3 HV-REVERSE REGULATION AND WINDING ARRANGEMENT

The initial parameters are:

Primary side voltage V_{1LL} = 400kV
Secondary side voltage V_{2LL} = 220kV
Power S = 400MVA
Magnetic flux B = 1.5T
Voltage per Turn VpT = 258V
Frequency f = 50Hz
Regulation range -15% to +15%
Current density J = 3A/mm^2
lamination factor of the core f_{FE} = 0.96
geometrical utilisation factor of the core η = 0.93
winding height h = 2000mm
winding space factor f_C = 0.5
width of the tertiary winding a = 20mm
insulation gap between core and tertiary winding g = 50mm

1. calculation of the core cross section and the core diameter:

$$A_{eff} = \frac{VpT}{4.44 \cdot f \cdot B} = \frac{258V}{4.44 \cdot 50Hz \cdot 1.5T} = 0.775m^2$$

$$D = \sqrt{\frac{A_{eff}}{\frac{\pi}{4} \cdot f_{FE} \cdot \eta}} = \sqrt{\frac{0.775m^2}{0.7}} = 1.05m$$

2. calculation of the needed turns for the different windings:

$$V_1 = \frac{V_{1LL}}{\sqrt{3}} = \frac{400kV}{\sqrt{3}} = 230.9kV \qquad V_2 = \frac{V_{2LL}}{\sqrt{3}} = \frac{220kV}{\sqrt{3}} = 127kV$$

$$N_c = \frac{V_2}{VpT} = \frac{127kV}{258V} = 493 \qquad N_c + N_s = \frac{V_1}{VpT} = \frac{230.9kV}{258V} = 895 \ \rightarrow N_S = 402$$

$$V_S = V_1 - V_2 = 230.9kV - 127kV = 103.9kV$$

For regulation of +15% U_R = 34.64kV therefore N_R will be:

$$N_R = \frac{V_R}{VpT} = \frac{34.64kV}{258V} = 135$$

3. calculation of the winding cross sections and the winding widths therefore the currents over the windings are needed.

$$I_{smax} = \frac{S}{\sqrt{3} \cdot V_{1LLmin}} = \frac{400MVA}{\sqrt{3} \cdot 340kV} = 679.24A$$

$$I_{smin} = \frac{S}{\sqrt{3} \cdot V_{1LLmin}} = \frac{400MVA}{\sqrt{3} \cdot 460kV} = 502.04A$$

$$I_2 = \frac{S}{\sqrt{3} \cdot V_{2LL}} = \frac{400MVA}{\sqrt{3} \cdot 220kV} = 1050A$$

$$I_{cmax} = I_2 - I_{Smin} = 1050A - 502.04A = 547.96A$$

$$A_S = \frac{I_{Smax}}{J \cdot f_C} = \frac{679.24A}{3\frac{A}{mm^2} \cdot 0.5} = 452.83mm^2 \qquad A_C = \frac{I_{Cmax}}{J \cdot f_C} = \frac{547.96A}{3\frac{A}{mm^2} \cdot 0.5} = 365.31mm^2$$

$$A_R = A_S$$

$$A_S = A_S \cdot N_S = 452.83mm^2 \cdot 402 = 182038mm^2 \quad \rightarrow A_C = A_C \cdot N_C = 180098mm^2$$

$$A_R = A_R \cdot N_R = 452.83mm^2 \cdot 135 = 61132mm^2$$

$$a_2 = \frac{A_S}{h} = \frac{182038mm^2}{2000mm} = 91mm \qquad a_1 = \frac{A_C}{h} = \frac{180098mm^2}{2000mm} = 90mm$$

$$a_3 = \frac{A_R}{h} = \frac{61132mm^2}{2000mm} = 30.6mm$$

4. calculation of the insulation gaps between the windings, therefore it is necessary to decide the BIL and SIL values for each winding then the DIL for each winding and with E = 6kV/mm the insulation gaps can be calculated.

Series winding: BIL = 1300kV, SIL = 1050kV and DIL = 583.3kV

$$g_2 = \frac{DIL}{E} = \frac{583.3kV}{6\frac{kV}{mm}} = 97.2mm$$

And for this winding arrangement g$_3$ equals g$_2$

Common winding: BIL = 850kV, SIL = 750kV and DIL = 416.7kV

$$g_1 = \frac{DIL}{E} = \frac{416.7kV}{6\frac{kV}{mm}} = 69.5mm$$

Regulation winding: BIL = 950kV, SIL = 750kV and DIL = 416.7kV

5. calculation of the short circuit impedance for 0% regulation (nominal tap position) N$_R$ = 0:

$$c = \frac{N_S}{N_S + N_R} = \frac{402}{402+0} = 1$$

$$\alpha = 1 - c + \frac{c^2}{3} = \frac{1}{3} \qquad \beta = (1-c)^2 = 0$$

$$\delta' = \frac{\frac{a_1}{3} + g_2 + \alpha \cdot a_2 + \beta \cdot \left(g_3 + \frac{a_3}{3}\right)}{10} = \frac{\frac{90mm}{3} + 97.2mm + \frac{1}{3} \cdot 91mm + 0}{10} = 15.75cm$$

$$K_R = 1 - \frac{1 - e^{\frac{-\pi \cdot h}{a_1 + g_2 + a_2}}}{\frac{\pi \cdot h}{a_1 + g_2 + a_2}} = 0.956 \qquad h_{eq} = \frac{h}{K_R \cdot 10} = 209.2cm$$

$$D_m = d_1 - \frac{2}{3} \cdot a_1 + \delta' \qquad with\ d_1 = \frac{D + 2 \cdot g + 2 \cdot a + 2 \cdot g_1}{10} = 132.84cm$$

$$D_m = 132.84cm - \frac{2}{3} \cdot 9cm + 15.75cm = 142.59cm$$

$$I_s = \frac{S}{\sqrt{3} \cdot V_{1LL}} = \frac{400MVA}{\sqrt{3} \cdot 400kV} = 577.35A$$

$$I_2 = \frac{S}{\sqrt{3} \cdot V_{2LL}} = \frac{400MVA}{\sqrt{3} \cdot 220kV} = 1050A$$

$$I_c = I_2 - I_S = 1050A - 577.35A = 472.65A$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{I_c N_c}{h_{eq} \cdot VpT} \delta' \cdot D_m$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{472.65A \cdot 493}{209.2cm \cdot 258V} 15.75cm \cdot 142.59cm = 12.12\%$$

$$uk_{AT} = u_k \cdot \frac{1}{F_C} \quad with\, F_C = \frac{\frac{V_{1LL}}{V_{2LL}}}{\frac{V_{1LL}}{V_{2LL}} - 1} = 2.22 \quad uk_{AT0\%} = 12.12\% \cdot \frac{1}{2.22} = 5.46\%$$

This value at 0% regulation presents the base value for the trend and means 100%

For different tap positions only step 5 needs to be change. For tap position of +15% we get in step 5:

$$c = \frac{N_S}{N_S + N_R} = \frac{402}{402 + 135} = 0.749$$

$$\alpha = 1 - c + \frac{c^2}{3} = 0.438 \qquad \beta = (1 - c)^2 = 0.063$$

$$\delta' = \frac{\frac{a_1}{3} + g_2 + \alpha \cdot a_2 + \beta \cdot \left(g_3 + \frac{a_3}{3}\right)}{10} = 17.38cm$$

$$K_R = 1 - \frac{1 - e^{\frac{-\pi \cdot h}{a_1 + g_2 + a_2}}}{\frac{\pi \cdot h}{a_1 + g_2 + a_2}} = 0.956 \qquad h_{eq} = \frac{h}{K_R \cdot 10} = 209.2cm$$

$$D_m = d_1 - \frac{2}{3} \cdot a_1 + \delta' \qquad with\, d_1 = \frac{D + 2 \cdot g + 2 \cdot a + 2 \cdot g_1}{10} = 132.84cm$$

$$D_m = 132.84cm - \frac{2}{3} \cdot 9cm + 17.38cm = 144.22cm$$

$$I_s = \frac{S}{\sqrt{3} \cdot V_{1LLmax}} = \frac{400MVA}{\sqrt{3} \cdot 460kV} = 502.04A$$

$$I_2 = \frac{S}{\sqrt{3} \cdot V_{2LL}} = \frac{400MVA}{\sqrt{3} \cdot 220kV} = 1050A$$

$$I_c = I_2 - I_S = 1050A - 577.35A = 547.96A$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{I_c N_c}{h_{eq} \cdot VpT} \delta' \cdot D_m$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{547.96A \cdot 493}{209.2cm \cdot 258V} 17.38cm \cdot 144.22cm = 15.68\%$$

$$uk_{AT} = u_k \cdot \frac{1}{F_C} \quad with\, F_C = \frac{\frac{V_{1LLmax}}{V_{2LL}}}{\frac{V_{1LLmax}}{V_{2LL}} - 1} = 1.92 \quad uk_{AT+15\%} = 15.68\% \cdot \frac{1}{1.92} = 8.17\%$$

The change of u_k between the two tap positions will be

$$\frac{uk_{AT+15\%}}{uk_{AT0\%}} \cdot 100\% = \frac{8.17\%}{5.46\%} \cdot 100\% = 149.6\%$$

This will be the next point for the trend and the same calculations must be done for all the other tap positions.

The second example is an Autotransformer with HV-regulation with variable flux and reverse regulation type and the following winding arrangement.

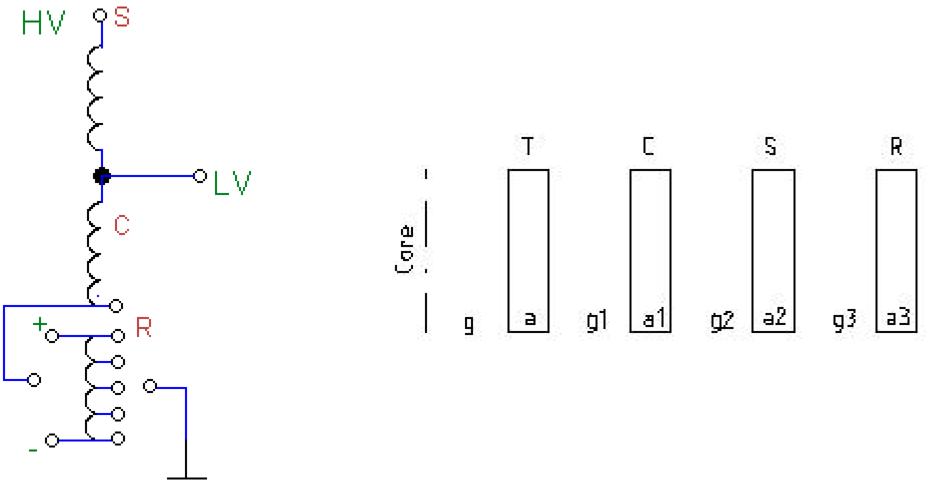


FIGURE 6-4 HV-REVERSE REGULATION AND WINDING ARRANGEMENT

The initial parameters are:

Primary side voltage $V_{1LL} = 400kV$
Secondary side voltage $V_{2LL} = 220kV$
Power S = 400MVA
Magnetic flux B = 1.5T
Voltage per Turn VpT = 258V
Frequency f = 50Hz
Regulation range -15% to +15%
Current density $J = 3A/mm^2$
lamination factor of the core $f_{FE} = 0.96$
geometrical utilisation factor of the core $\eta = 0.93$
winding height h = 2000mm
winding space factor $f_C = 0.5$
width of the tertiary winding a = 20mm
insulation gap between core and tertiary winding g = 50mm

Step 1 will produce the same results as before therefore D=1.05m. From step 2 we can take $N_S = 402$ and with chapter 4 we get for $N_C = 555$ and $N_R = 185$.

From step 3 we can take the values of the currents and get for the cross sections and width of the windings:

$$A_S = \frac{I_{Smax}}{J \cdot f_C} = \frac{679.24A}{3\frac{A}{mm^2} \cdot 0.5} = 452.83mm^2 \qquad A_C = \frac{I_{Cmax}}{J \cdot f_C} = \frac{547.96A}{3\frac{A}{mm^2} \cdot 0.5} = 365.31mm^2$$

$$A_R = A_C$$

$$A_S = A_S \cdot N_S = 452.83mm^2 \cdot 402 = 182038mm^2 \quad \rightarrow A_C = A_C \cdot N_C = 202747mm^2$$

$$A_R = A_R \cdot N_R = 365.31mm^2 \cdot 185 = 67582mm^2$$

$$a_2 = \frac{A_S}{h} = \frac{182038mm^2}{2000mm} = 91mm \qquad a_1 = \frac{A_C}{h} = \frac{202747mm^2}{2000mm} = 101.4mm$$

$$a_3 = \frac{A_R}{h} = \frac{67582mm^2}{2000mm} = 33.8mm$$

4. calculation of the insulation gaps between the windings, therefore it is necessary to decide the BIL and SIL values for each winding then the DIL for each winding and with E = 6kV/mm the insulation gaps can be calculated.

Series winding: BIL = 1300kV, SIL = 1050kV and DIL = 583.3kV

$$g_2 = \frac{DIL}{E} = \frac{583.3kV}{6\frac{kV}{mm}} = 97.2mm$$

And for this winding arrangement g_3 equals g_2

Common winding: BIL = 850kV, SIL = 750kV and DIL = 416.7kV

$$g_1 = \frac{DIL}{E} = \frac{416.7kV}{6\frac{kV}{mm}} = 69.5mm$$

Regulation winding: BIL = 450kV, SIL = 375kV and DIL = 208.3kV

5. calculation of the short circuit impedance for 0% regulation (nominal tap position):

$$N_C + N_R = \frac{V_2}{Vpt} = \frac{127kV}{258V} = 493 \qquad 493 - N_C = N_R \rightarrow N_R = -62$$

$$c = \frac{N_C}{N_C + N_R \cdot (-1)} = \frac{555}{555 + 62} = 0.9$$

$$\alpha = 1 - c + \frac{c^2}{3} = 0.37 \qquad \beta = (1-c)^2 = 0.01$$

$$\delta' = \frac{\frac{a_1}{3} + g_2 + \alpha \cdot a_2 + \beta \cdot \left(g_3 + \frac{a_3}{3}\right)}{10} = 16.58cm$$

$$K_R = 1 - \frac{1 - e^{\frac{-\pi \cdot h}{a_1 + g_2 + a_2}}}{\frac{\pi \cdot h}{a_1 + g_2 + a_2}} = 0.954 \qquad h_{eq} = \frac{h}{K_R \cdot 10} = 209.6cm$$

$$D_m = d_1 - \frac{2}{3} \cdot a_1 + \delta' \qquad with\ d_1 = \frac{D + 2 \cdot g + 2 \cdot a + 2 \cdot g_1}{10} = 132.9cm$$

$$D_m = 132.9cm - \frac{2}{3} \cdot 10.14cm + 16.58cm = 142.72cm$$

$$I_s = \frac{S}{\sqrt{3} \cdot V_{1LL}} = \frac{400MVA}{\sqrt{3} \cdot 400kV} = 577.35A$$

$$I_2 = \frac{S}{\sqrt{3} \cdot V_{2LL}} = \frac{400MVA}{\sqrt{3} \cdot 220kV} = 1050A$$

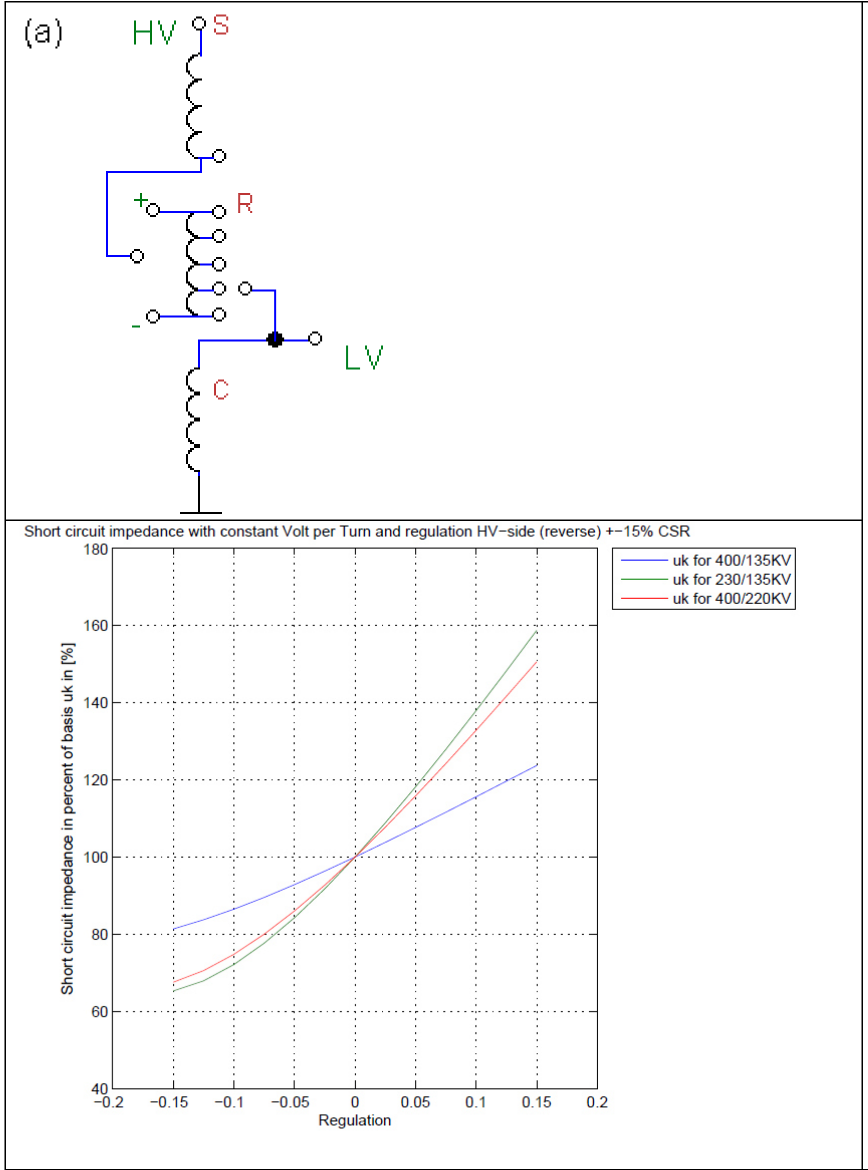
$$I_c = I_2 - I_S = 1050A - 577.35A = 472.65A$$

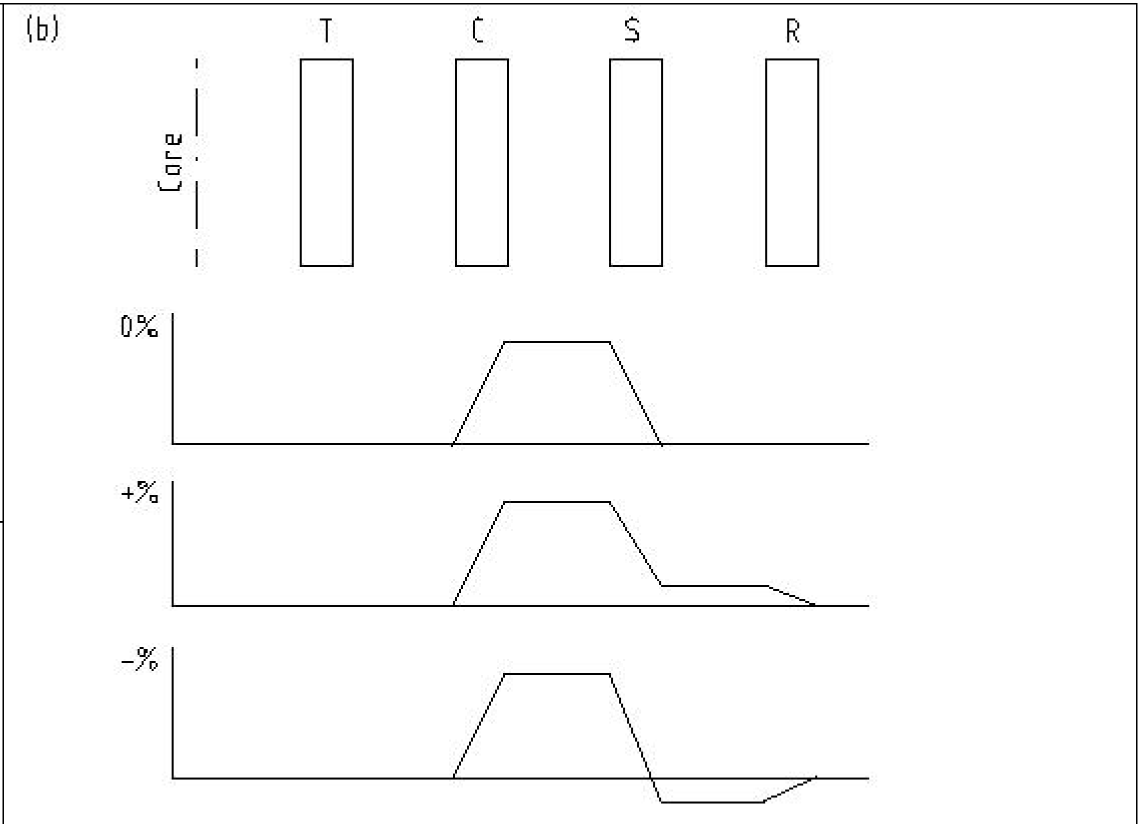
$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{I_c N_c}{h_{eq} \cdot VpT} \delta' \cdot D_m$$

$$u_k = 1.25 \cdot 10^{-3} \cdot \frac{577.35A \cdot 402}{209.6cm \cdot 258V} 16.58cm \cdot 142.72cm = 12.7\%$$

$$uk_{AT} = u_k \cdot \frac{1}{F_C} \quad with\ F_C = \frac{\frac{V_{1LL}}{V_{2LL}}}{\frac{V_{1LL}}{V_{2LL}} - 1} = 2.22 \quad uk_{AT0\%} = 12.7\% \cdot \frac{1}{2.22} = 5.72\%$$

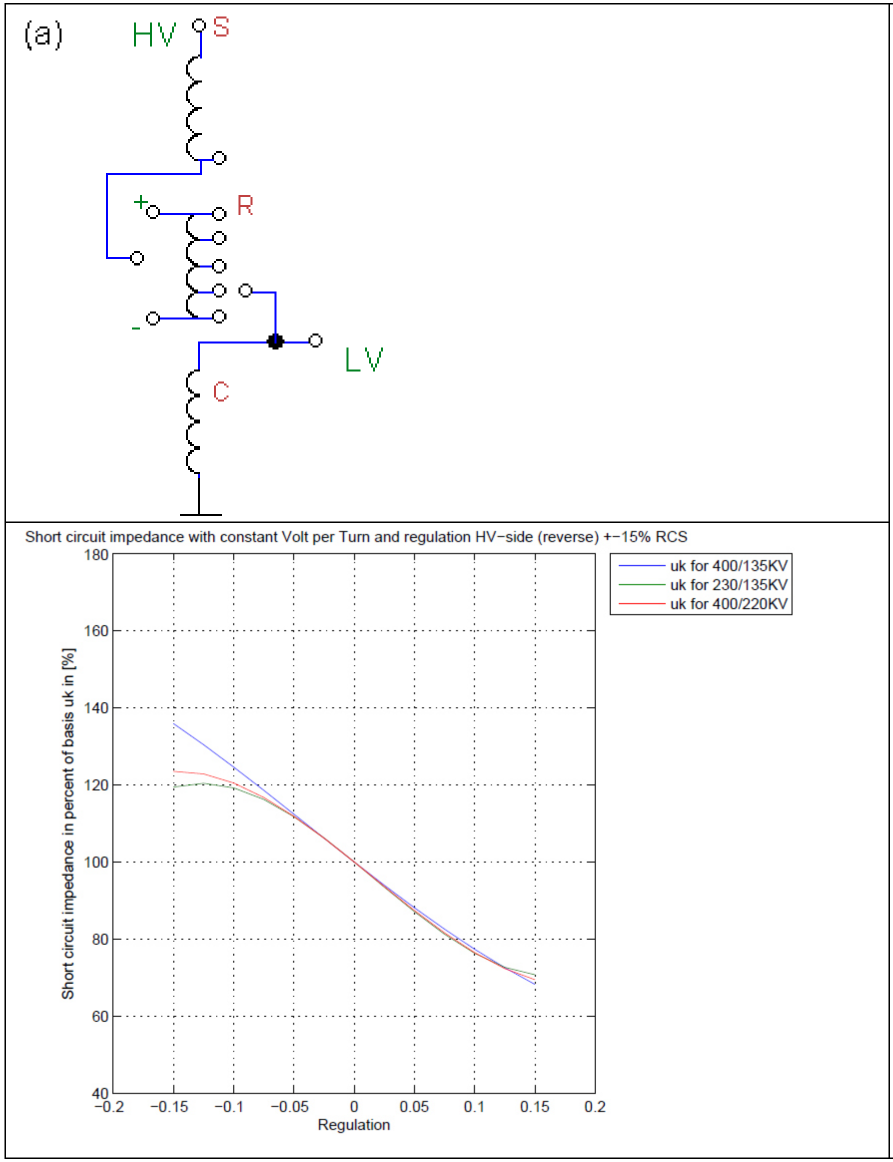
This value at 0% regulation presents the base value for the trend and means 100%
The calculations for the other tap positions follow the same principle again.

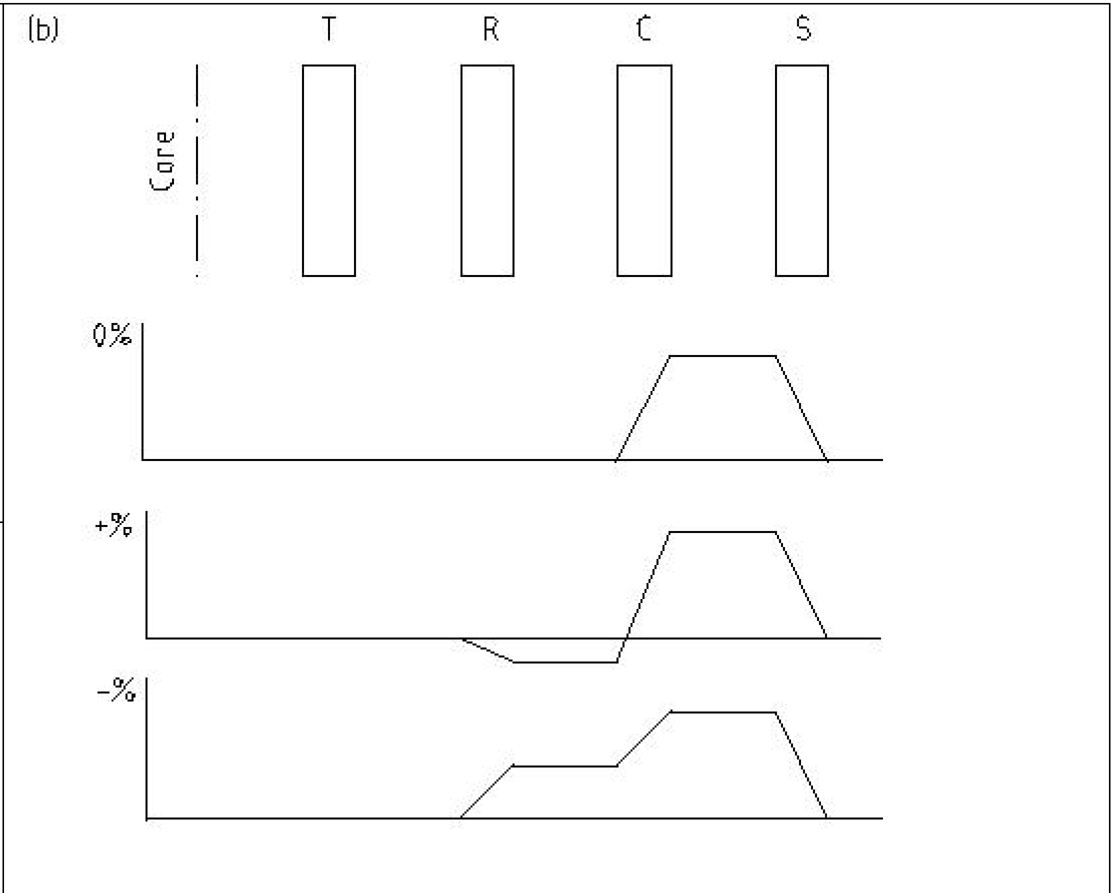




	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
standard	65.29	100	158.8	67.55	100	150.6	81.35	100	123.7
1.5*CS	63.43	100	155.1	66.36	100	147.4	81.6	100	122
1.5*SR	70.82	100	161.8	71.94	100	153	83.05	100	124.7

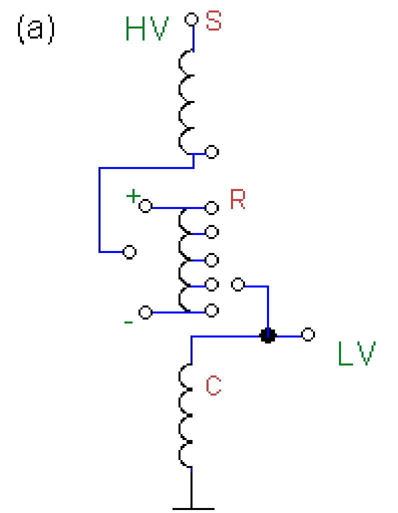
TABLE 7 HV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX CSR

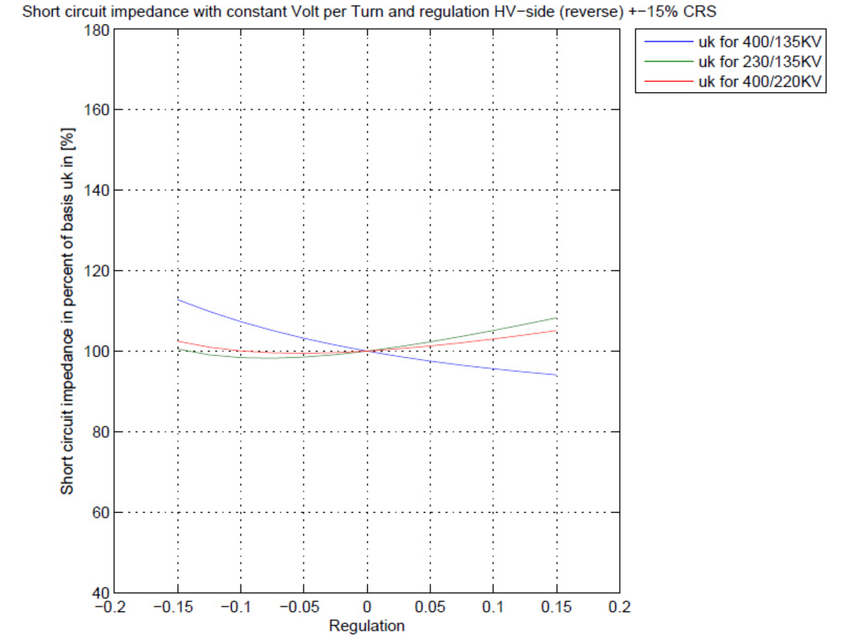


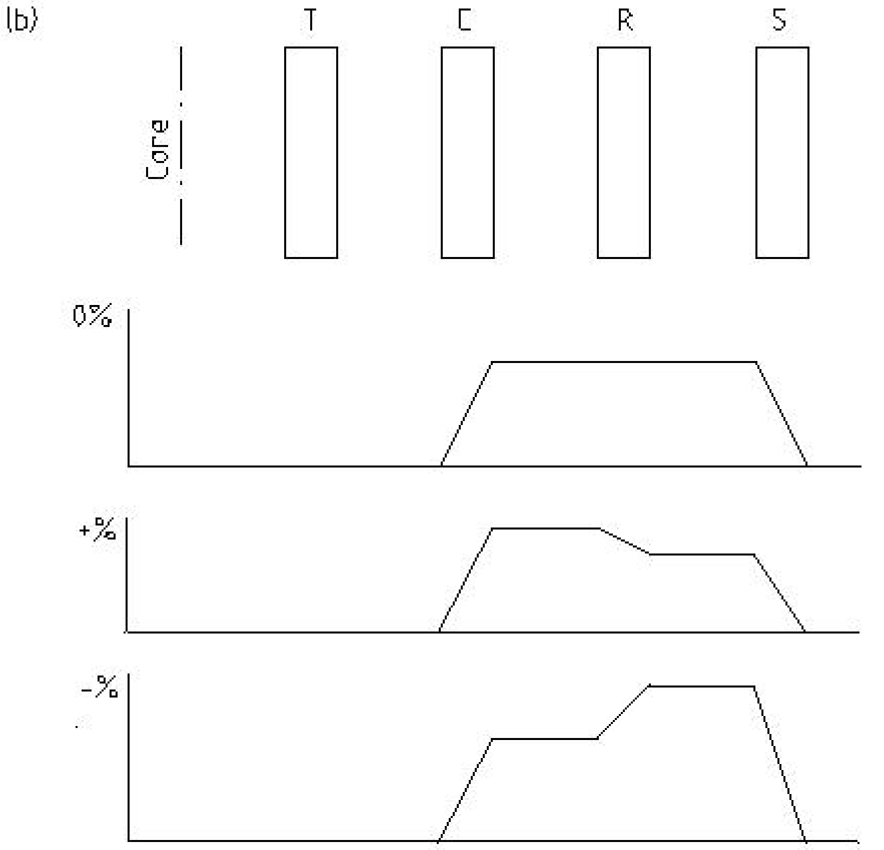


	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
standard	119.5	100	70.73	123.5	100	69.44	135.9	100	68.21
1.5*RC	122.5	100	78.52	126.2	100	75.39	137.3	100	70.13
1.5*CS	116.4	100	67.94	120.6	100	67.90	133.9	100	68.23

TABLE 8 HV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX RCS

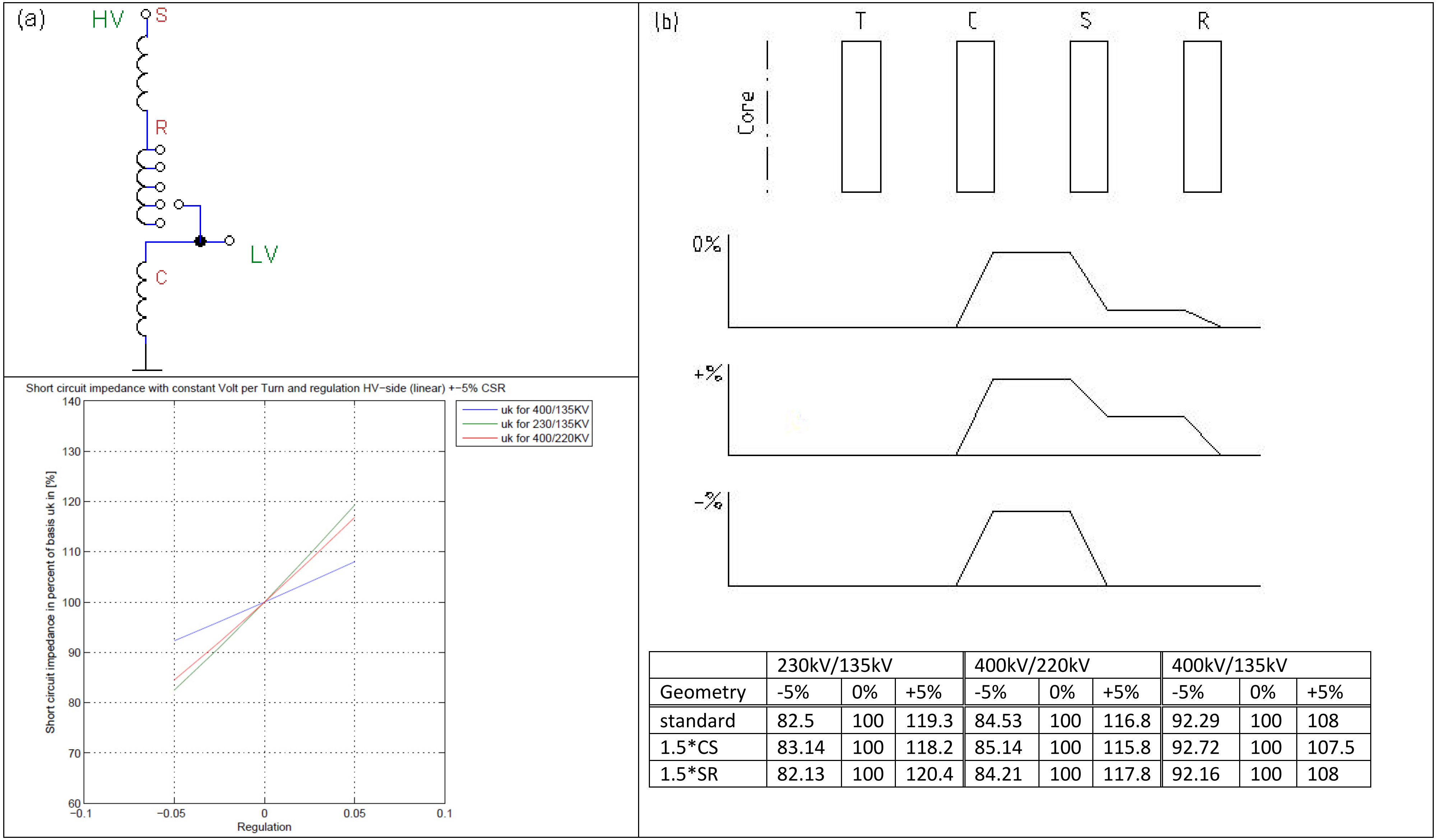






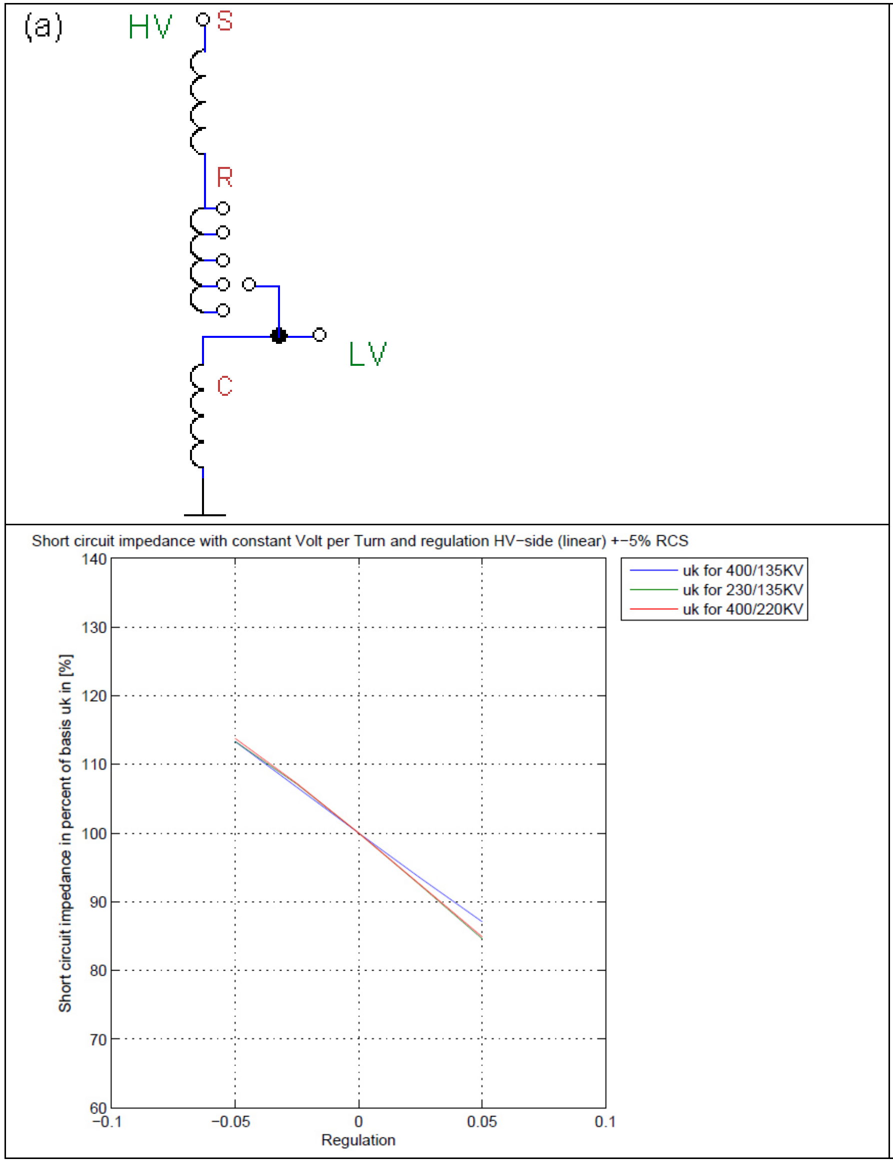
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
standard	100.5	100	108.3	102.5	100	105.1	112.8	100	94.09
1.5*CR	94	100	112.9	96.56	100	109.2	108.8	100	96.64
1.5*RS	109.1	100	103.2	110	100	100.6	117.4	100	91.38

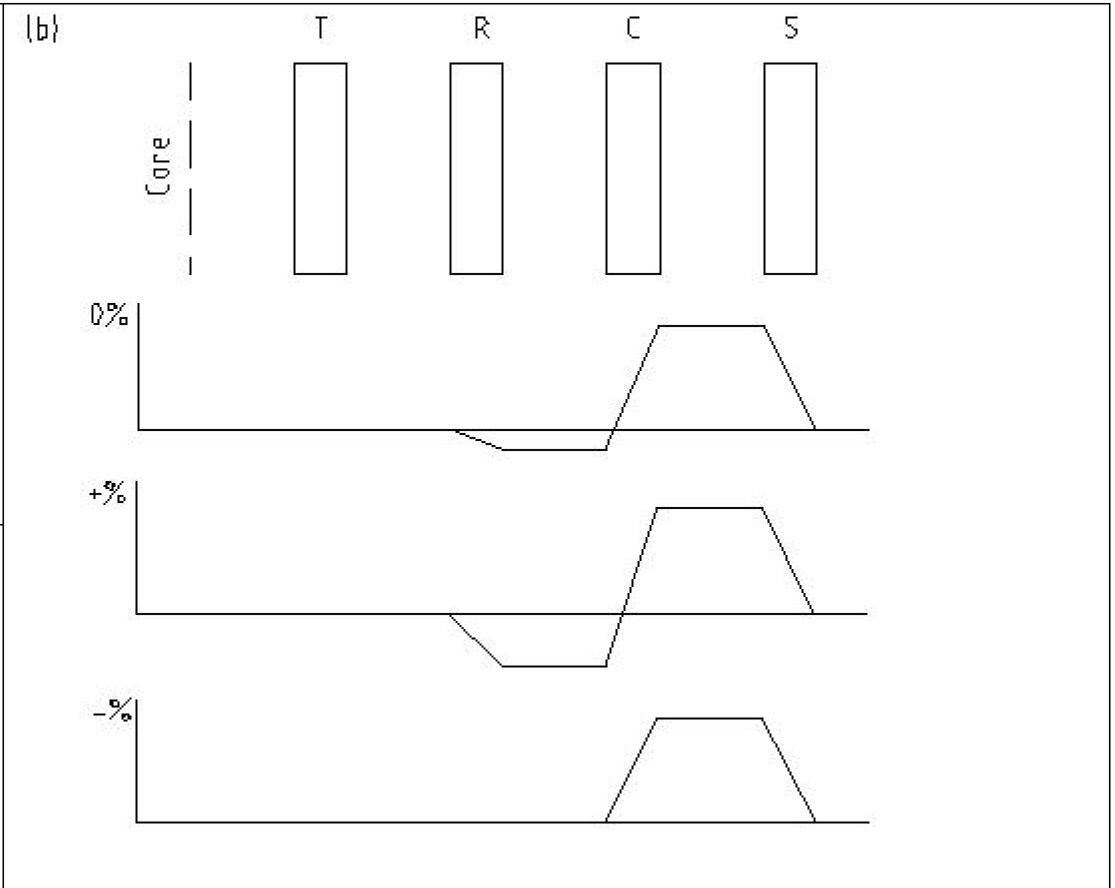
TABLE 9 HV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX CRS



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
standard	82.5	100	119.3	84.53	100	116.8	92.29	100	108
1.5*CS	83.14	100	118.2	85.14	100	115.8	92.72	100	107.5
1.5*SR	82.13	100	120.4	84.21	100	117.8	92.16	100	108

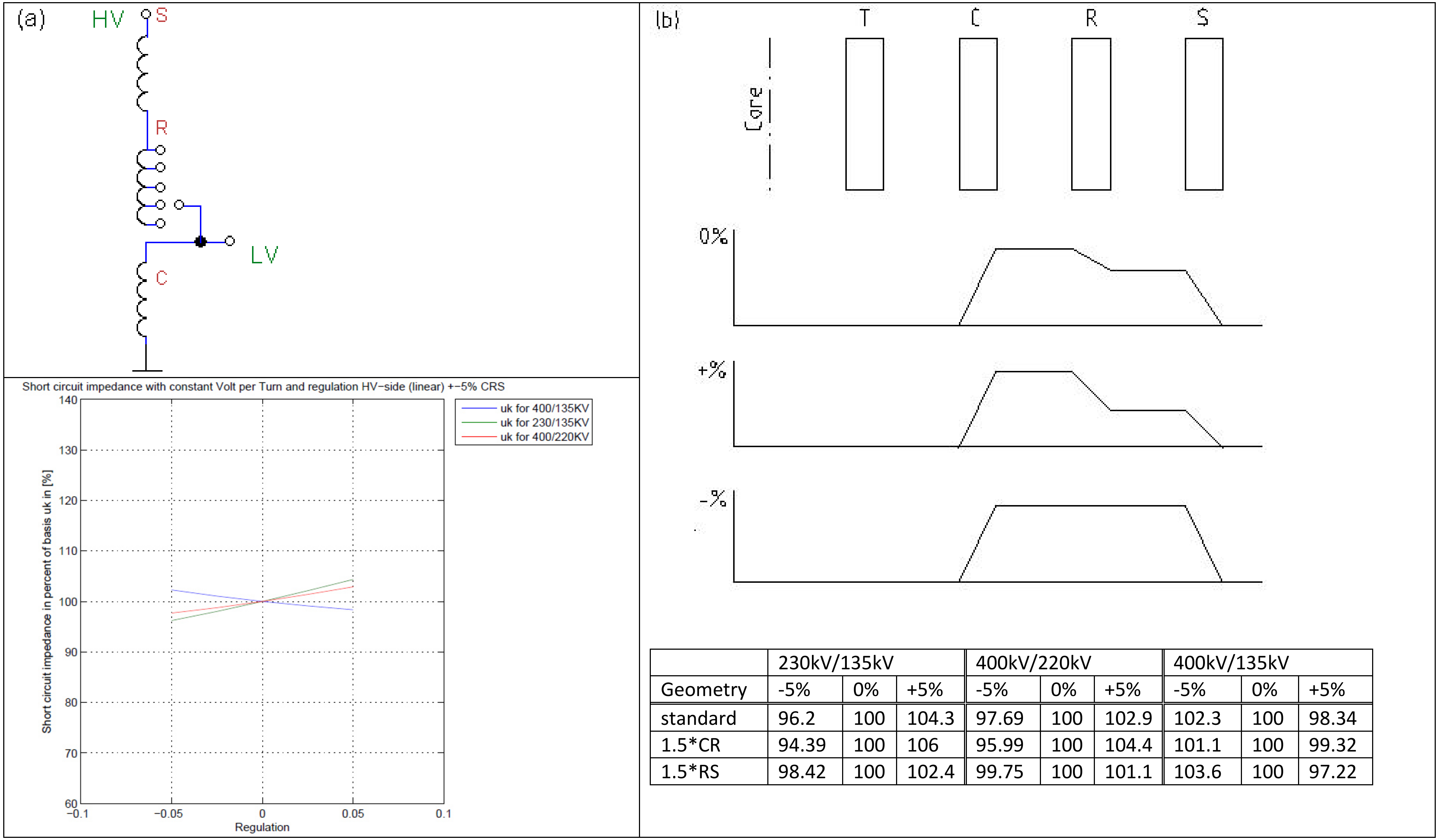
TABLE 10 HV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX CSR





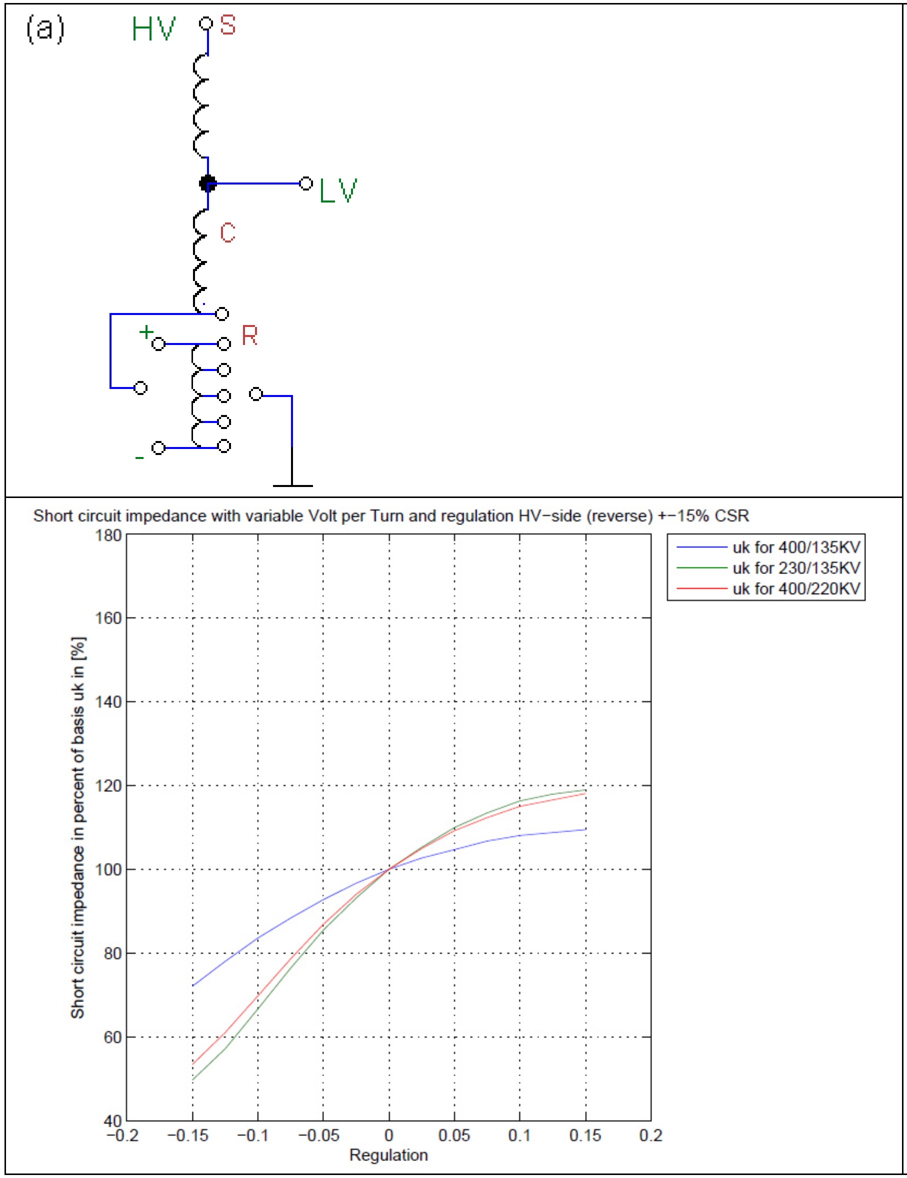
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
standard	113.3	100	84.61	113.8	100	84.88	113.3	100	87.07
1.5*RC	114.7	100	84.1	115	100	84.45	113.9	100	86.9
1.5*CS	112.1	100	85.94	112.7	100	85.55	112.7	100	87.49

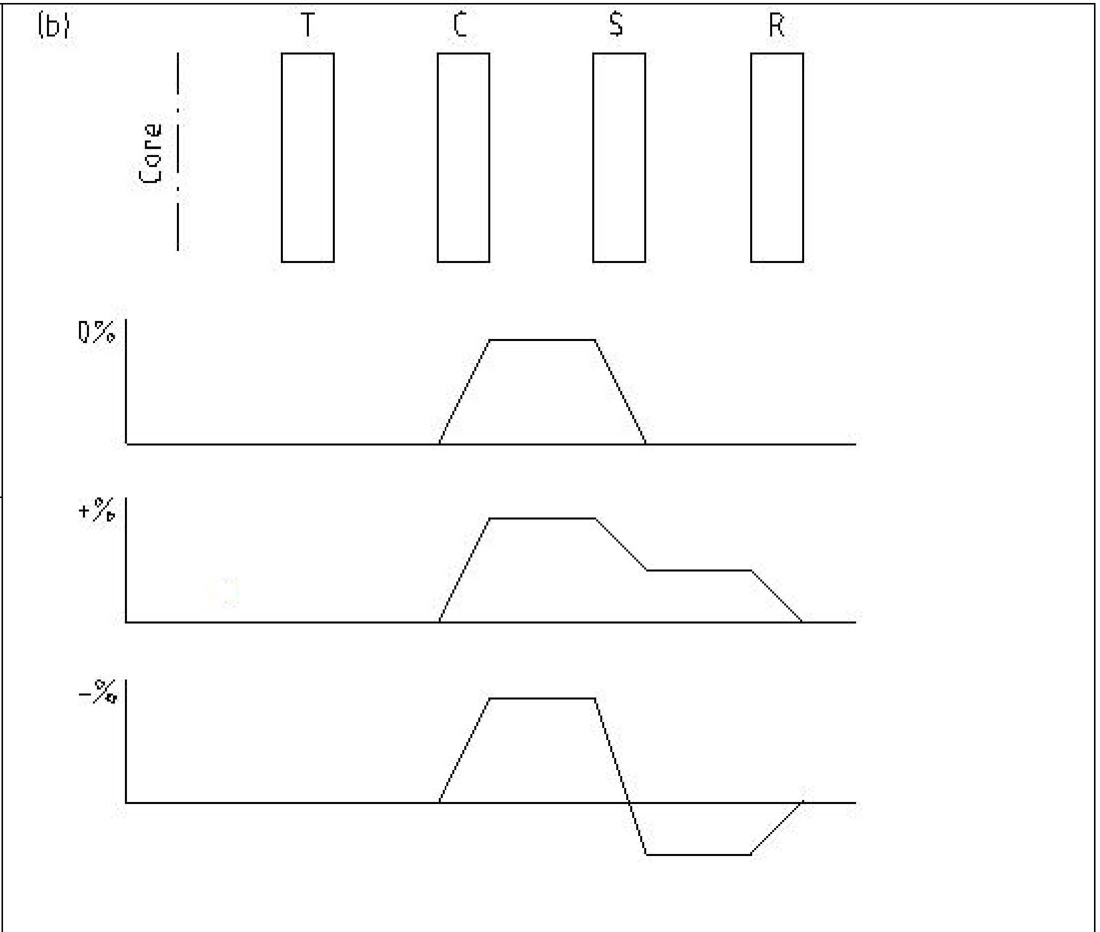
TABLE 11 HV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX RCS



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
standard	96.2	100	104.3	97.69	100	102.9	102.3	100	98.34
1.5*CR	94.39	100	106	95.99	100	104.4	101.1	100	99.32
1.5*RS	98.42	100	102.4	99.75	100	101.1	103.6	100	97.22

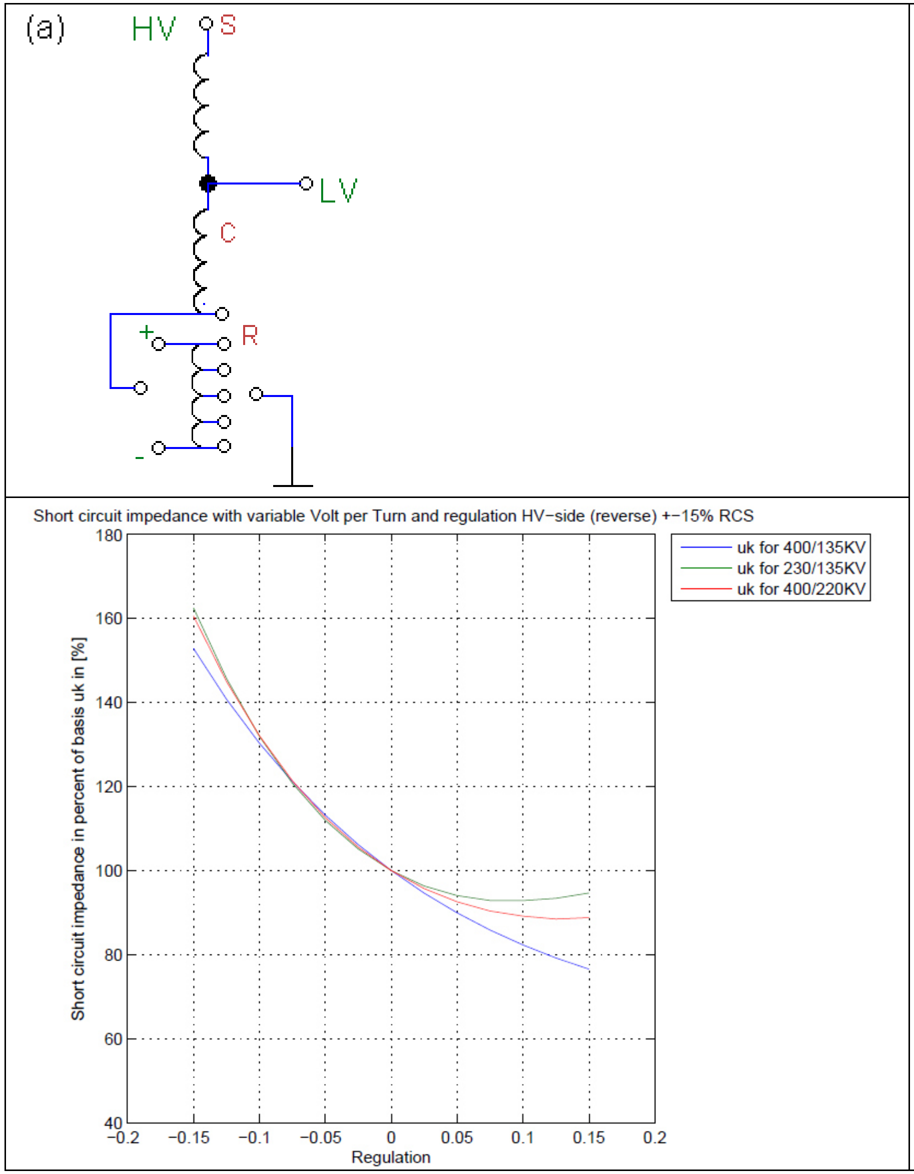
TABLE 12 HV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX CRS

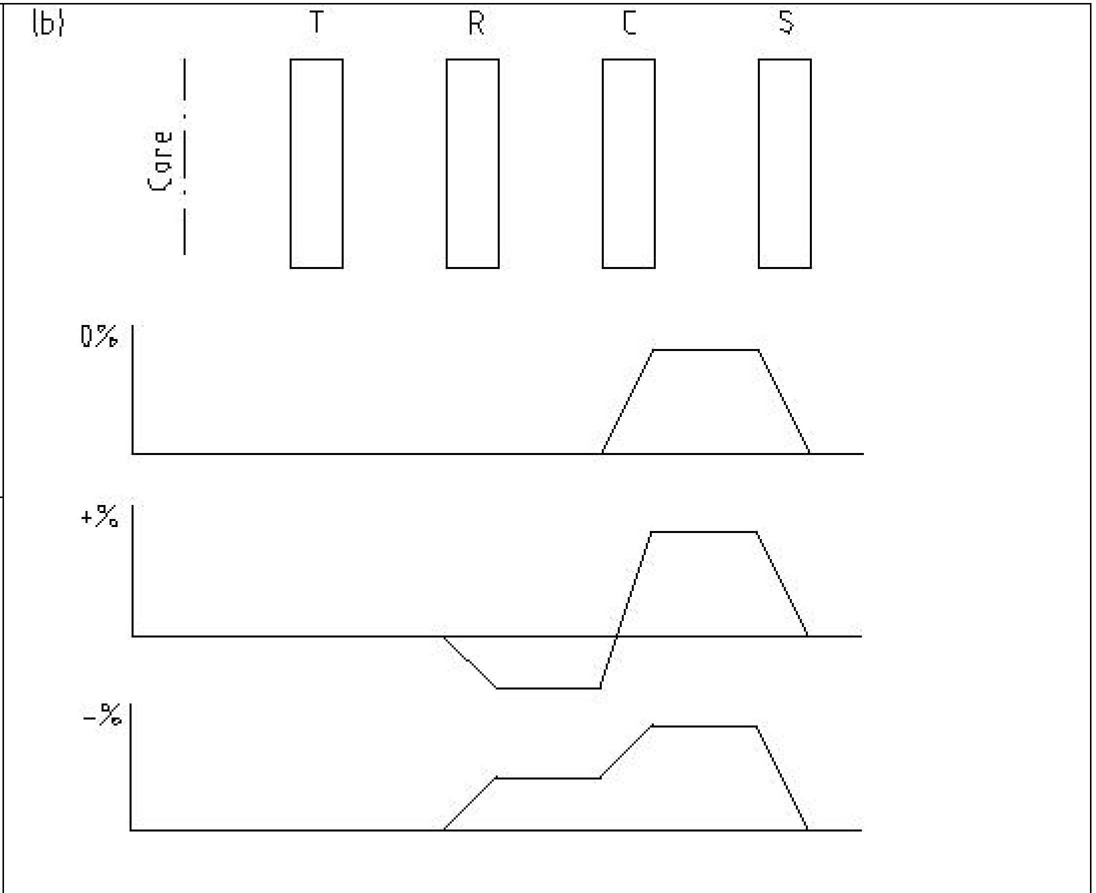




	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	49.68	100	118.9	53.41	100	118.1	72.07	100	109.5
1.5*CS	48.56	100	117.1	52.75	100	116.4	72.53	100	108.3
1.5*SR	53.54	100	120.7	56.68	100	119.6	73.53	100	110.2

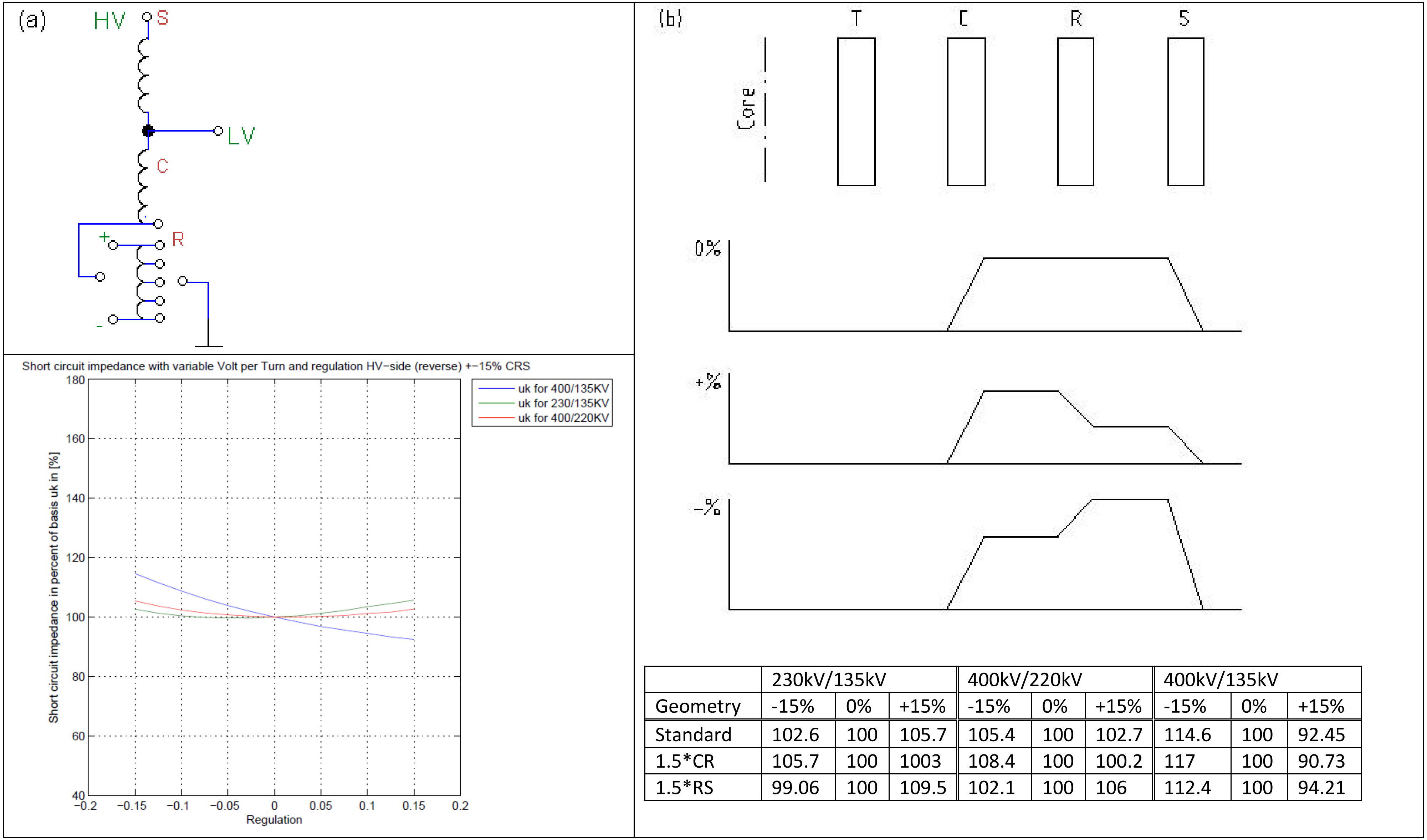
TABLE 13 HV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX CSR





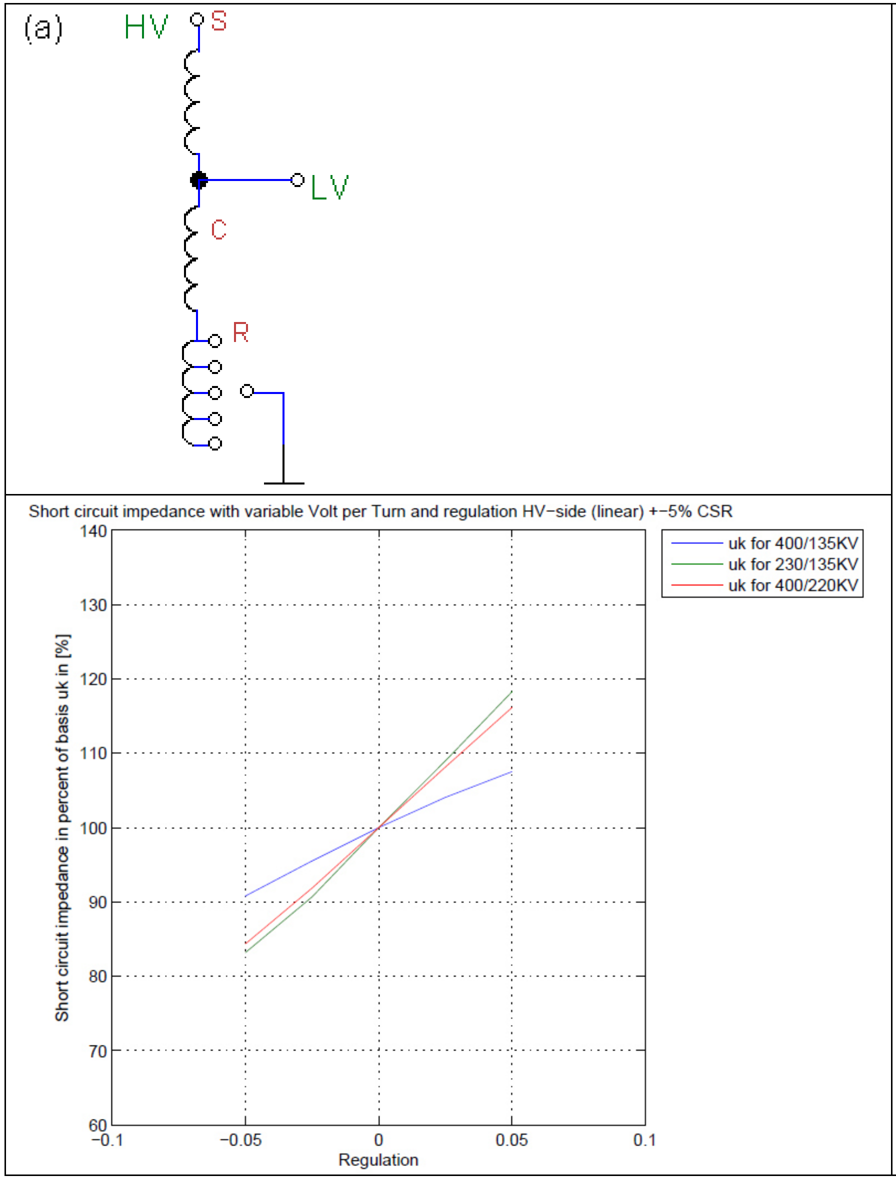
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	162.5	100	94.66	160.6	100	88.8	152.8	100	76.54
1.5*RC	165	100	103.7	163	100	95.78	154.2	100	78.64
1.5*CS	157.7	100	90.84	156.2	100	86.22	150.4	100	76.39

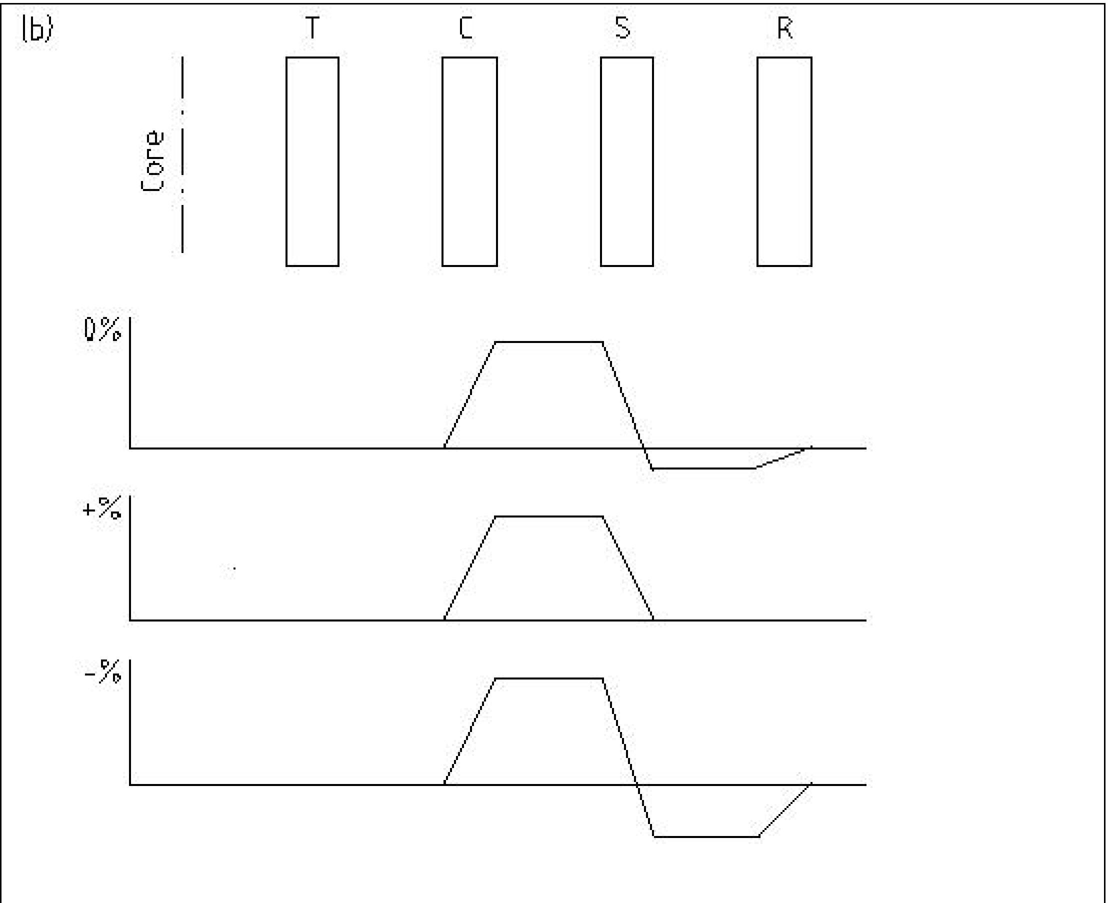
TABLE 14 HV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX RCS



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	102.6	100	105.7	105.4	100	102.7	114.6	100	92.45
1.5*CR	105.7	100	1003	108.4	100	100.2	117	100	90.73
1.5*RS	99.06	100	109.5	102.1	100	106	112.4	100	94.21

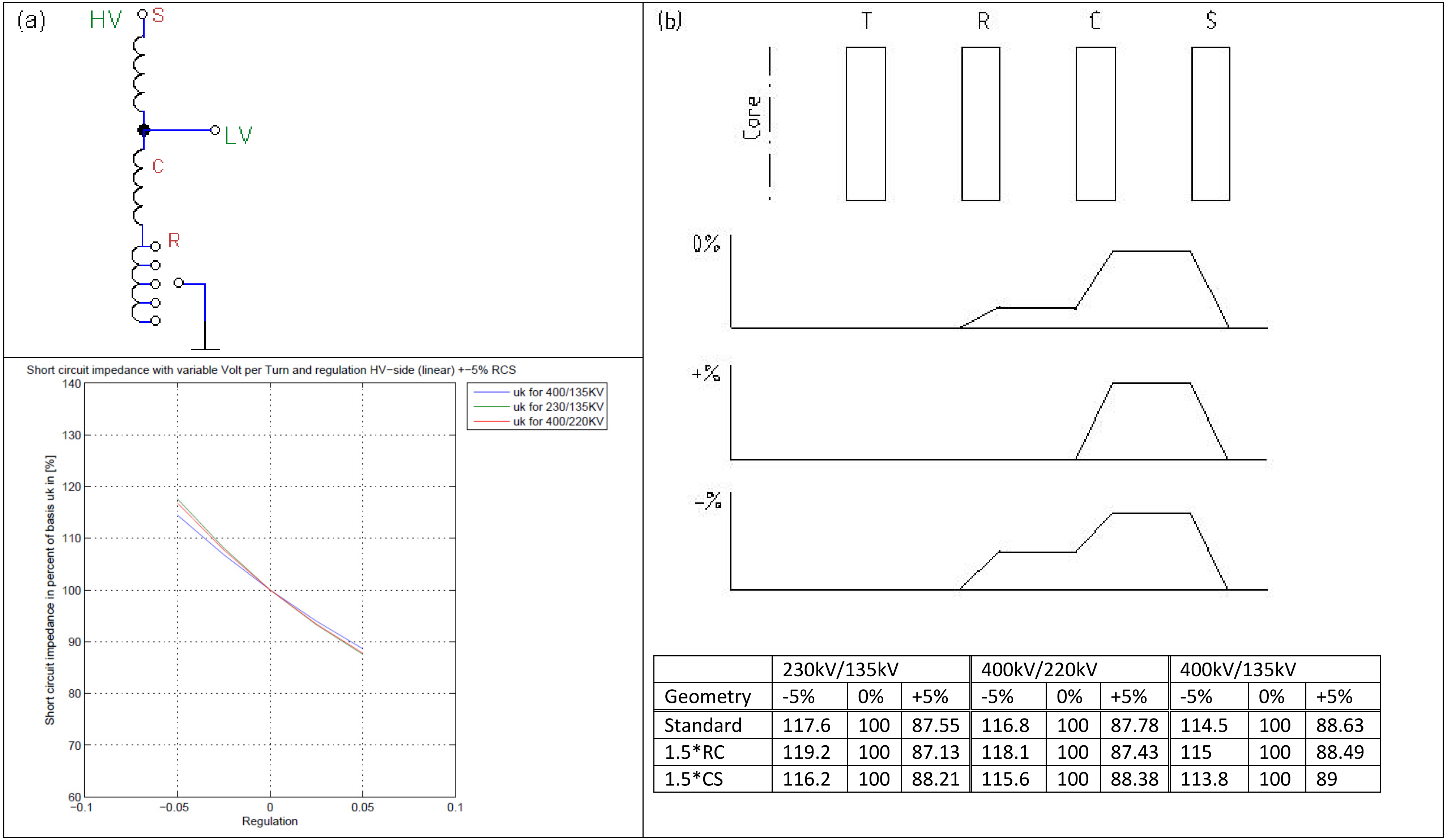
TABLE 15 HV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX CRS





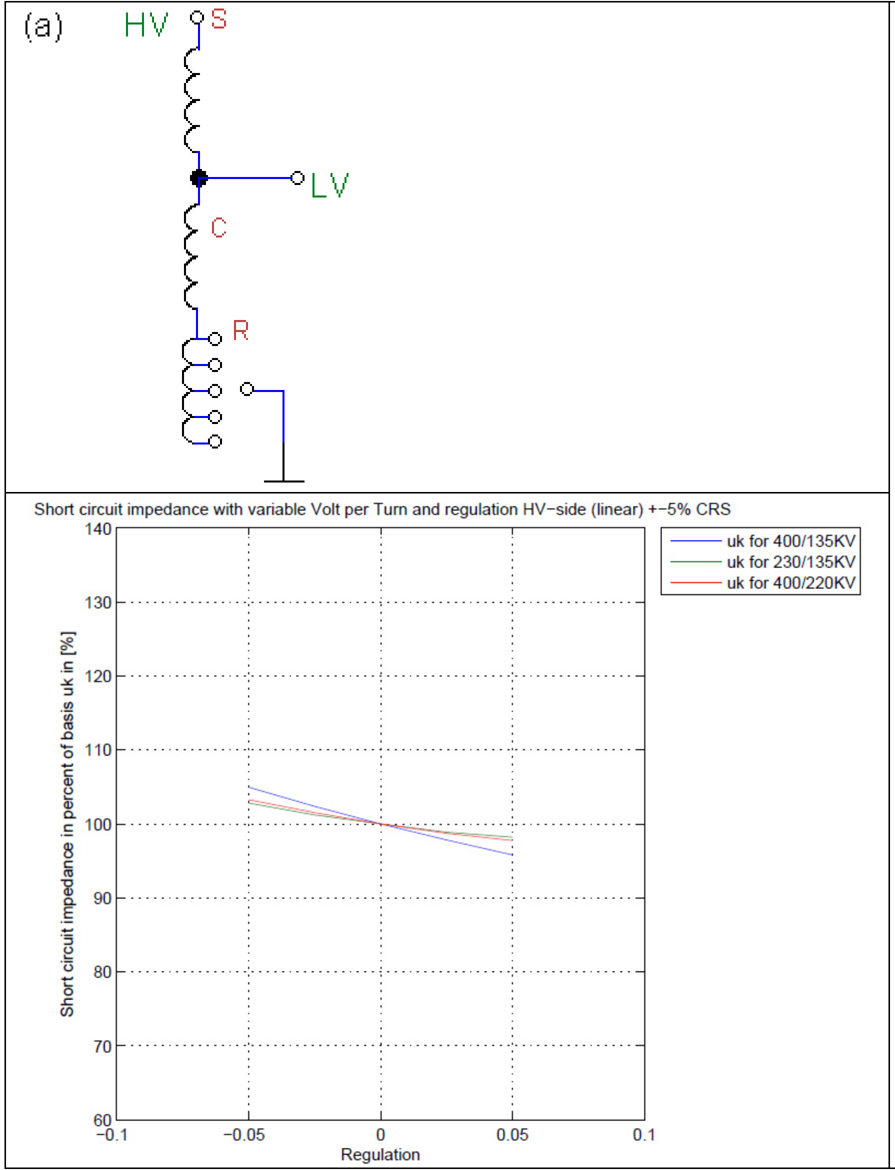
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	80.19	100	119	82.03	100	116.7	90.07	100	107.7
1.5*CS	79.15	100	118.6	81.4	100	116.3	90.21	100	107.3
1.5*SR	83.19	100	118.3	84.35	100	116.1	90.8	100	107.5

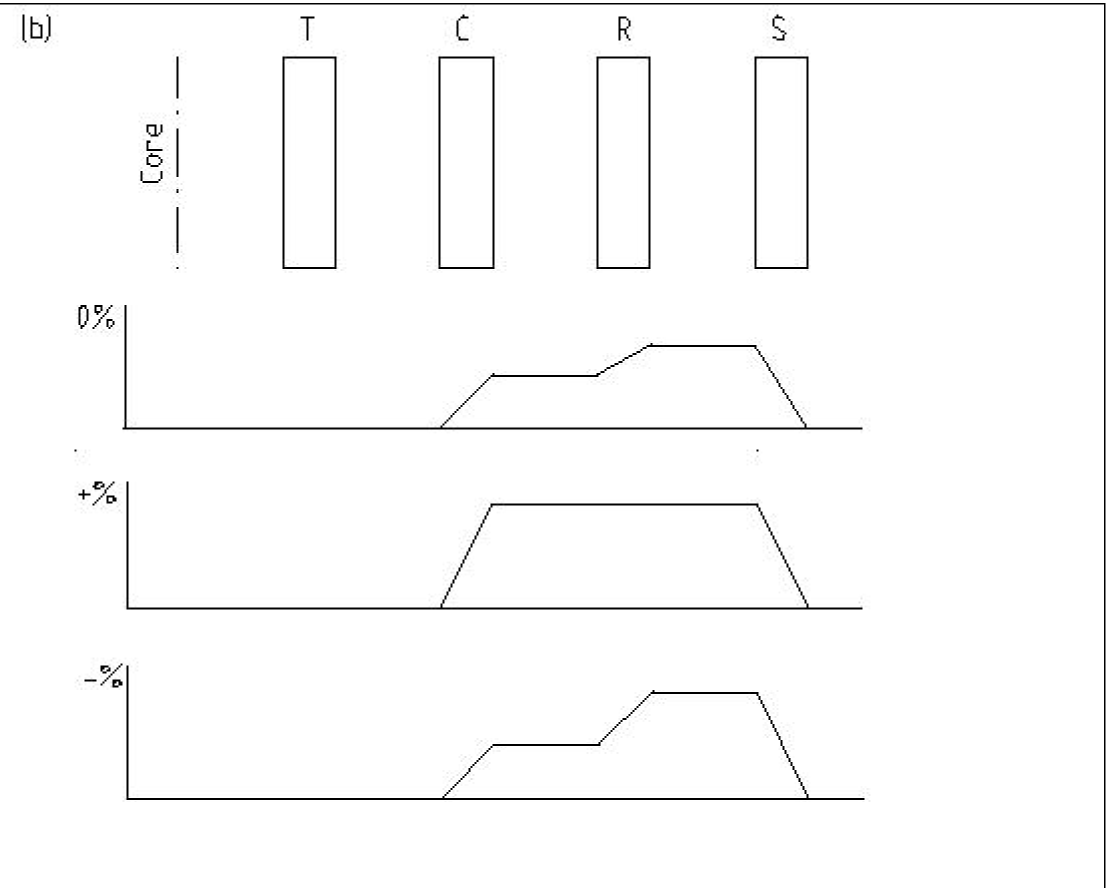
TABLE 16 HV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX CSR



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	117.6	100	87.55	116.8	100	87.78	114.5	100	88.63
1.5*RC	119.2	100	87.13	118.1	100	87.43	115	100	88.49
1.5*CS	116.2	100	88.21	115.6	100	88.38	113.8	100	89

TABLE 17 HV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX RCS





	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	102.8	100	98.2	103.3	100	97.75	105	100	95.8
1.5*CR	103.8	100	97.31	104.2	100	96.91	105.6	100	95.2
1.5*RS	101.8	100	99.18	102.3	100	98.65	104.3	100	96.35

TABLE 18 HV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX CRS

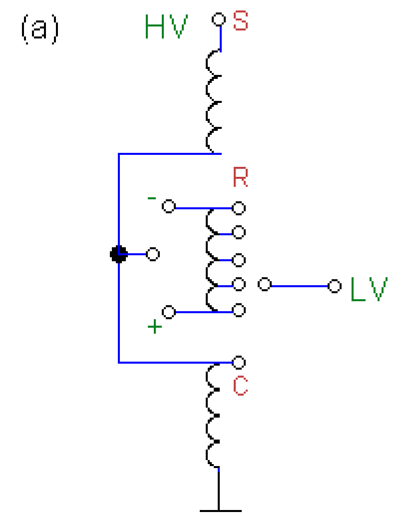
For regulation the high voltage side the winding arrangement CRS produces the lowest variation of the short circuit impedance over the regulation range. Because from the ampere turn diagram we see that when the regulation winding is used no auxiliary gap is produced because the winding is in between the others. So the geometry arrangement for the leakage flux changes not really.

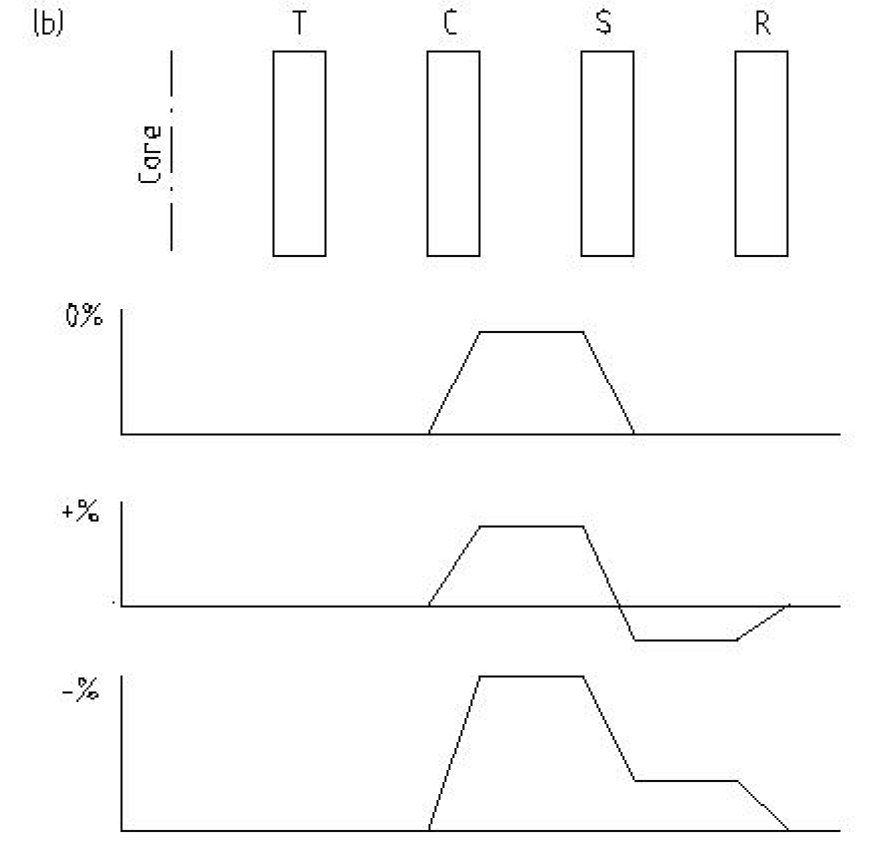
For some winding arrangements for regulation range greater 5% and especially smaller transformer ratios, at the maximum tap position the trend is not really linear and makes a curve. Therefor maybe the results at this tap positions are not similar to the real values. In fact the short circuit impedance increases or decreases for this tap position but the change of u_k is not as big as the factor F_C increases or decreases and so the trend gets a gently gradient.

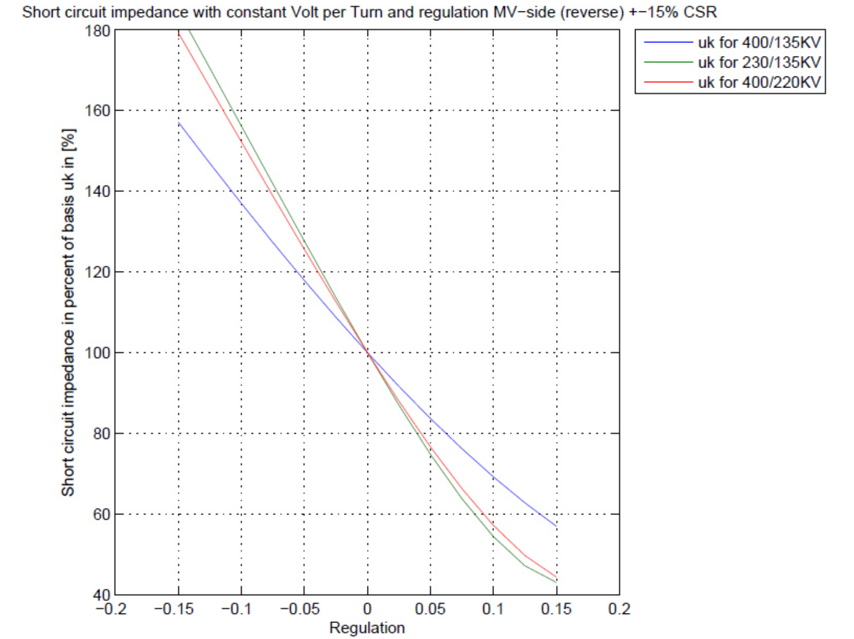
The transformer ratio has also some influence in the variation of the short circuit impedance. For a small transformer ratio the variation of u_k increases for CSR. Is responsible for a little increase in RCS and reduces the variation for the arrangement CRS. The trend of u_k for linear regulation follows them of the reverse type which is clear with a look at the ampere turn diagrams for the different winding arrangements.

The tables under the ampere turn diagrams show the influence of different insulation gap widths between the windings. The geometry “standard” shows the normal gap widths. In the other lines always one gap is increased by the factor 1.5 and the others are kept constant. The results show that there is little influence of different gap widths only variation of the gap close to the regulation winding has more influence on them.

Finally the best results for the short circuit impedance are possible for HV-regulation with the winding arrangement CRS where the regulation winding is placed in between the common and series winding.

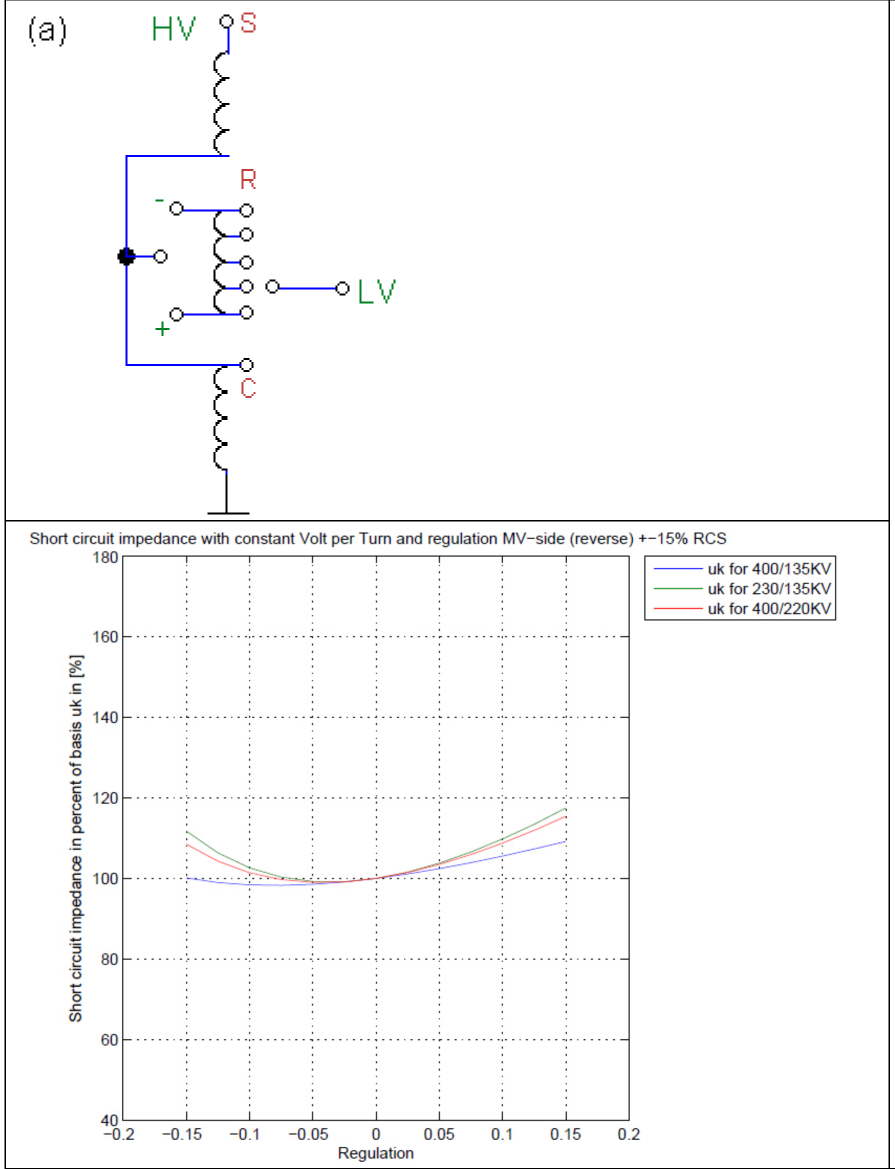


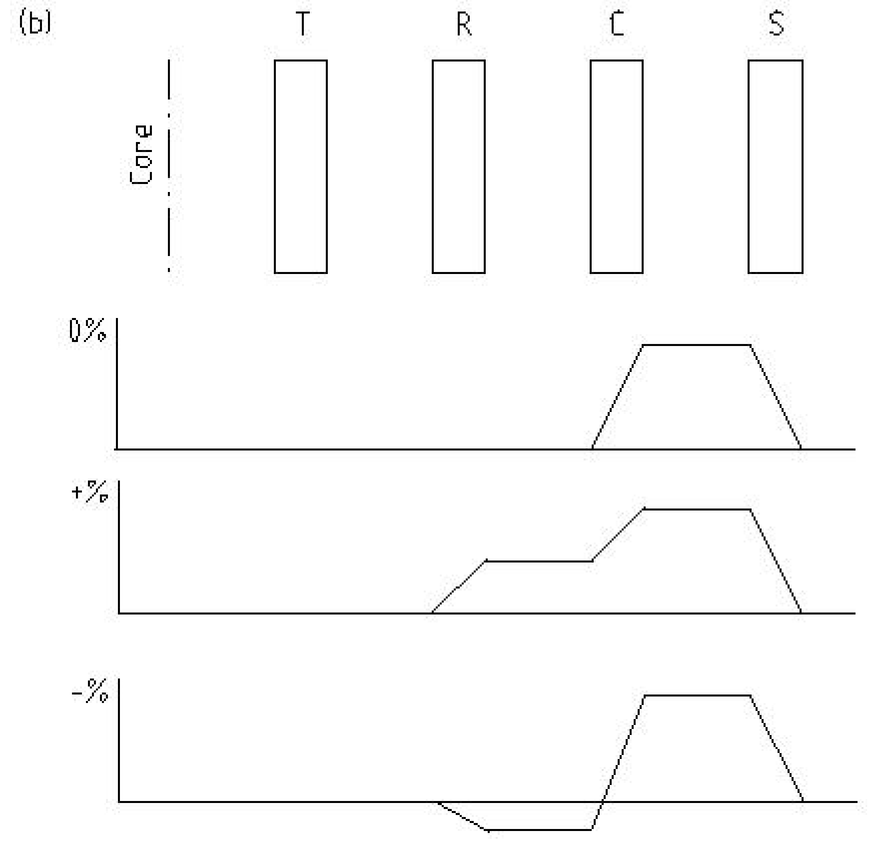




	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	184.78	100	42.99	179.28	100	44.34	157.1	100	56.91
1.5*CS	181.61	100	40.14	176.41	100	42.48	155.33	100	56.91
1.5*SR	187.45	100	49.72	181.57	100	49.3	158.2	100	58.37

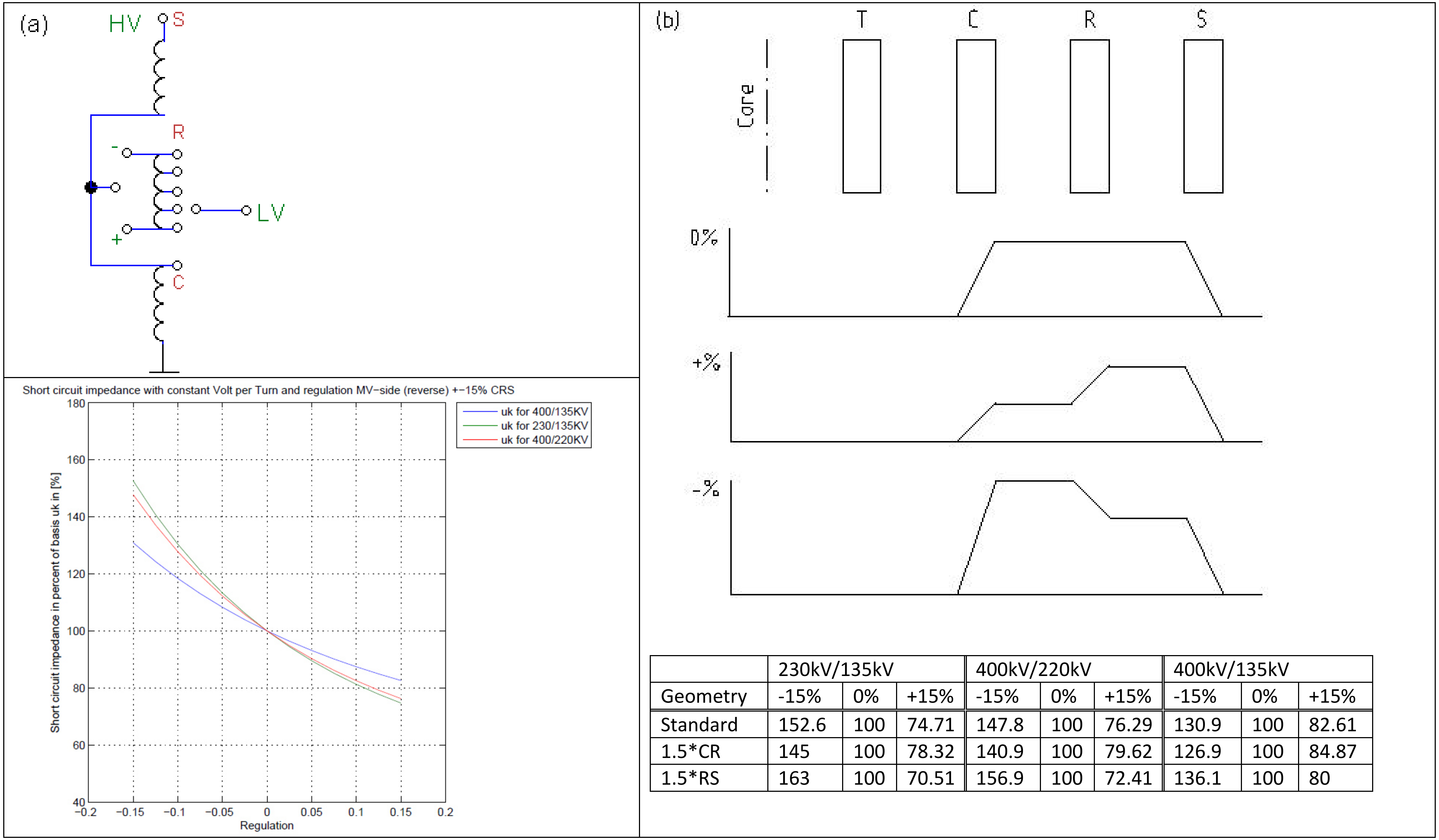
TABLE 19 LV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX CSR





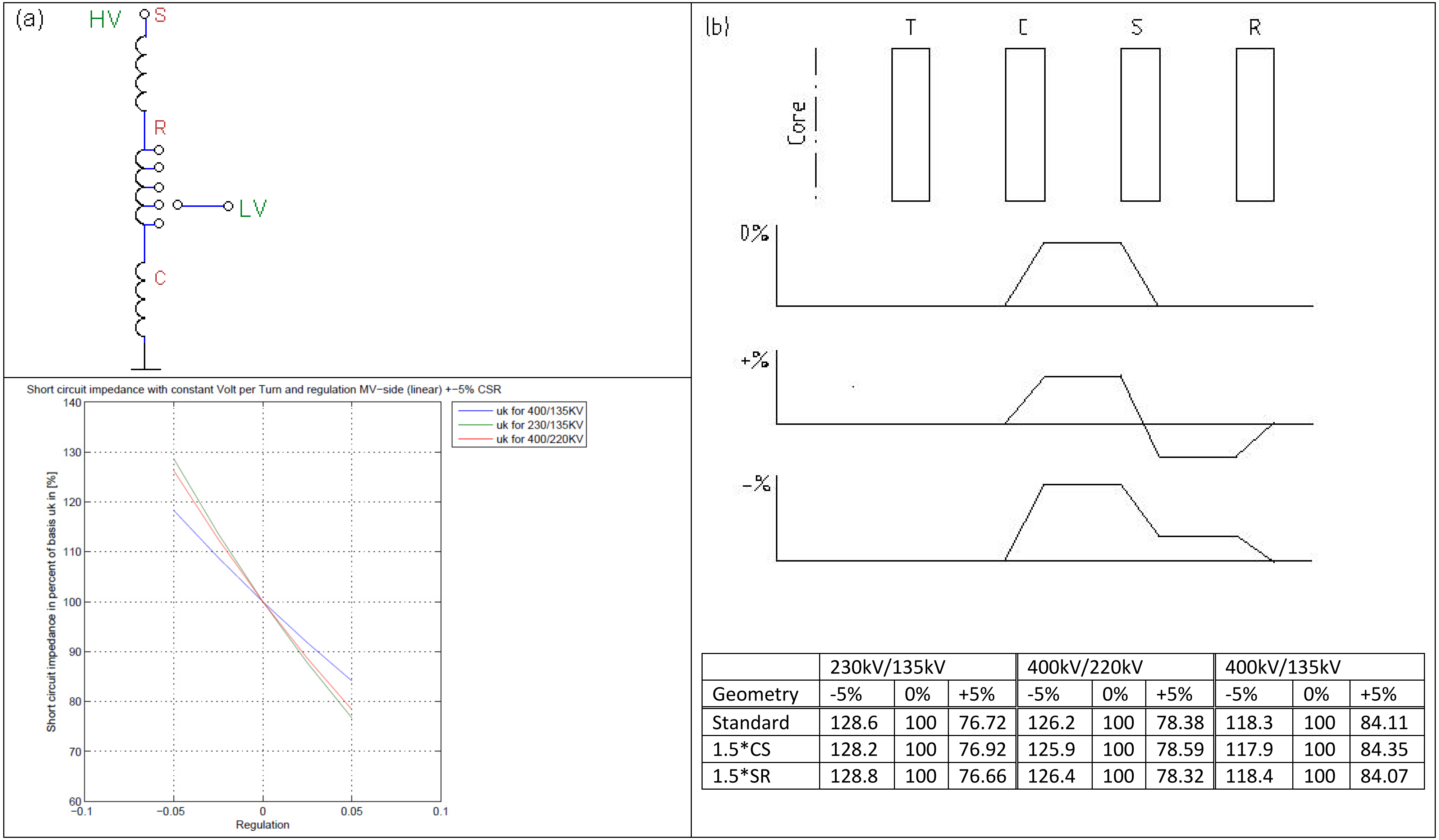
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	111.7	100	117.5	108.5	100	115.4	100.1	100	109.2
1.5*RC	119.3	100	121.6	114.7	100	118.7	102.5	100	110.5
1.5*CS	109.4	100	113.9	106.8	100	112.4	100.1	100	107.6

TABLE 20 LV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX RCS



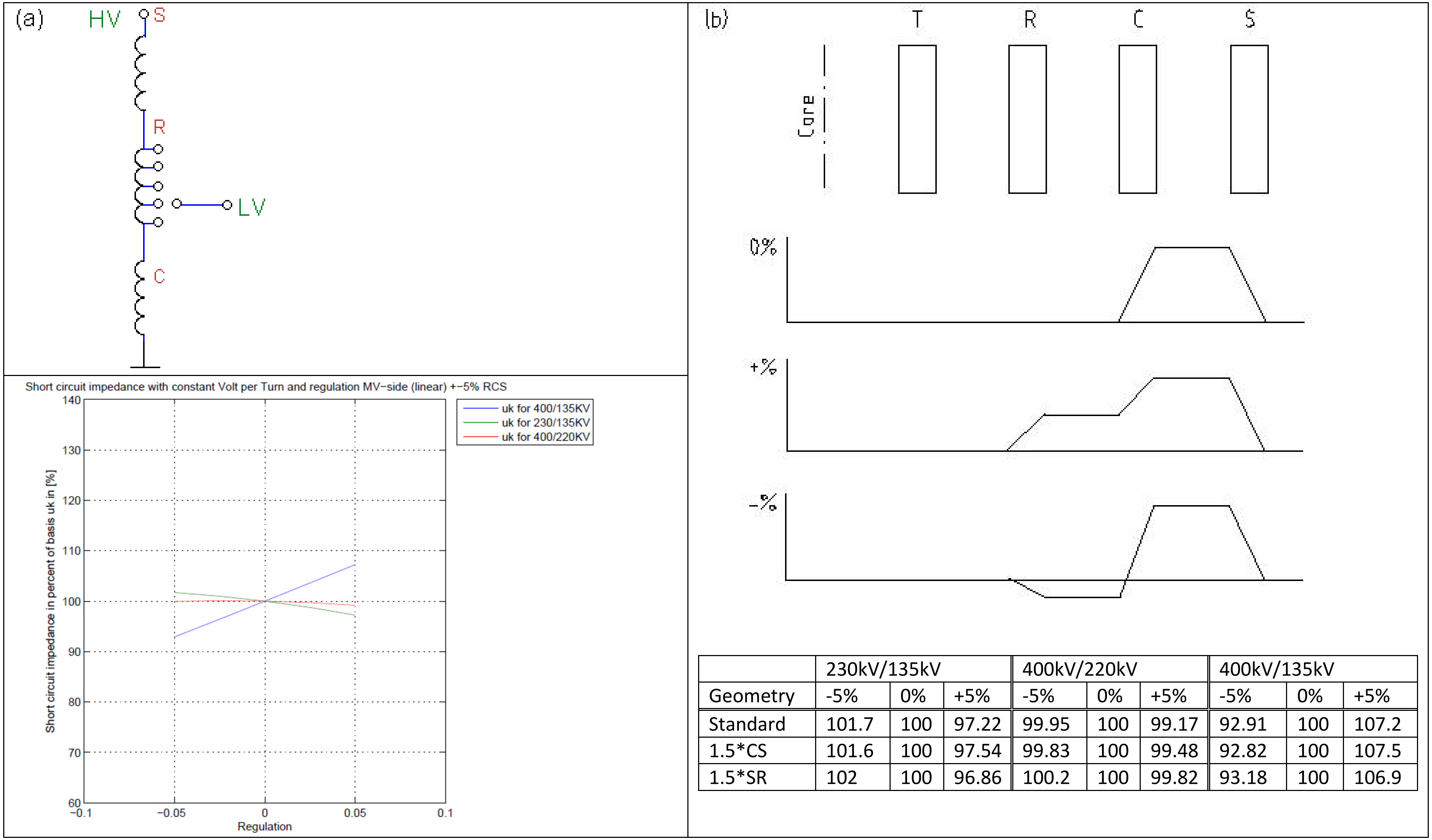
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	152.6	100	74.71	147.8	100	76.29	130.9	100	82.61
1.5*CR	145	100	78.32	140.9	100	79.62	126.9	100	84.87
1.5*RS	163	100	70.51	156.9	100	72.41	136.1	100	80

TABLE 21 LV-SIDE REGULATION WITH REVERSE TYPE AND CONSTANT FLUX CRS



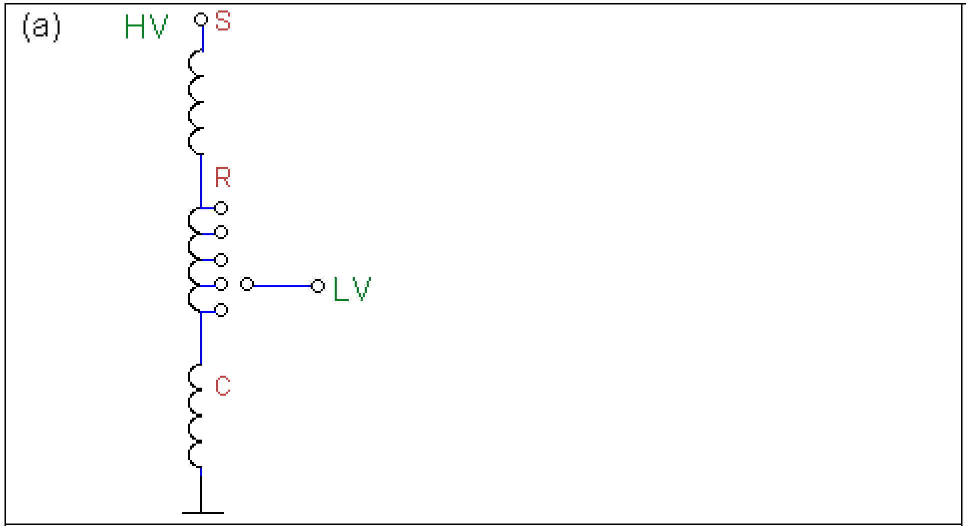
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	128.6	100	76.72	126.2	100	78.38	118.3	100	84.11
1.5*CS	128.2	100	76.92	125.9	100	78.59	117.9	100	84.35
1.5*SR	128.8	100	76.66	126.4	100	78.32	118.4	100	84.07

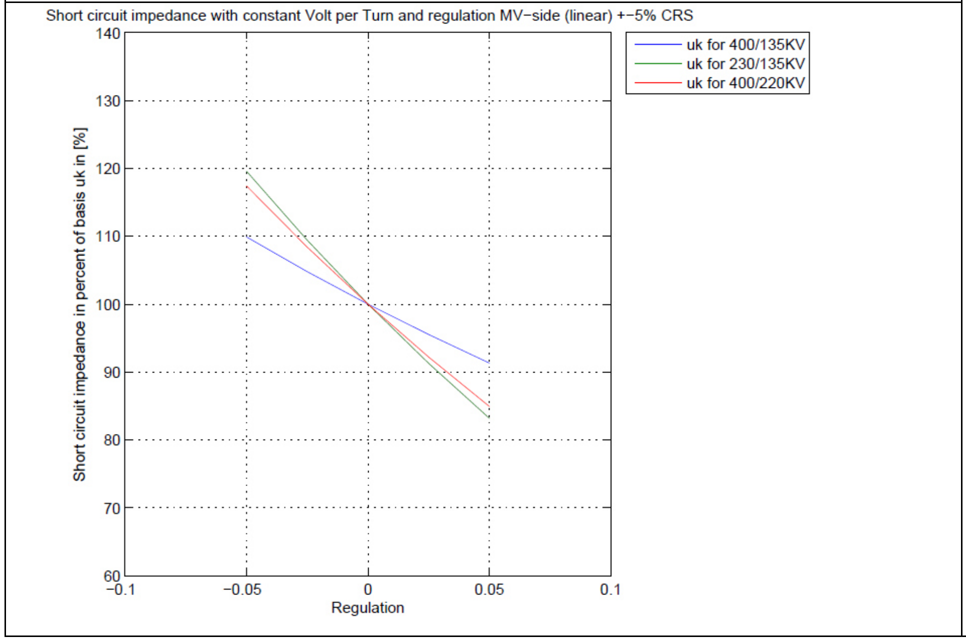
TABLE 22 LV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX CSR

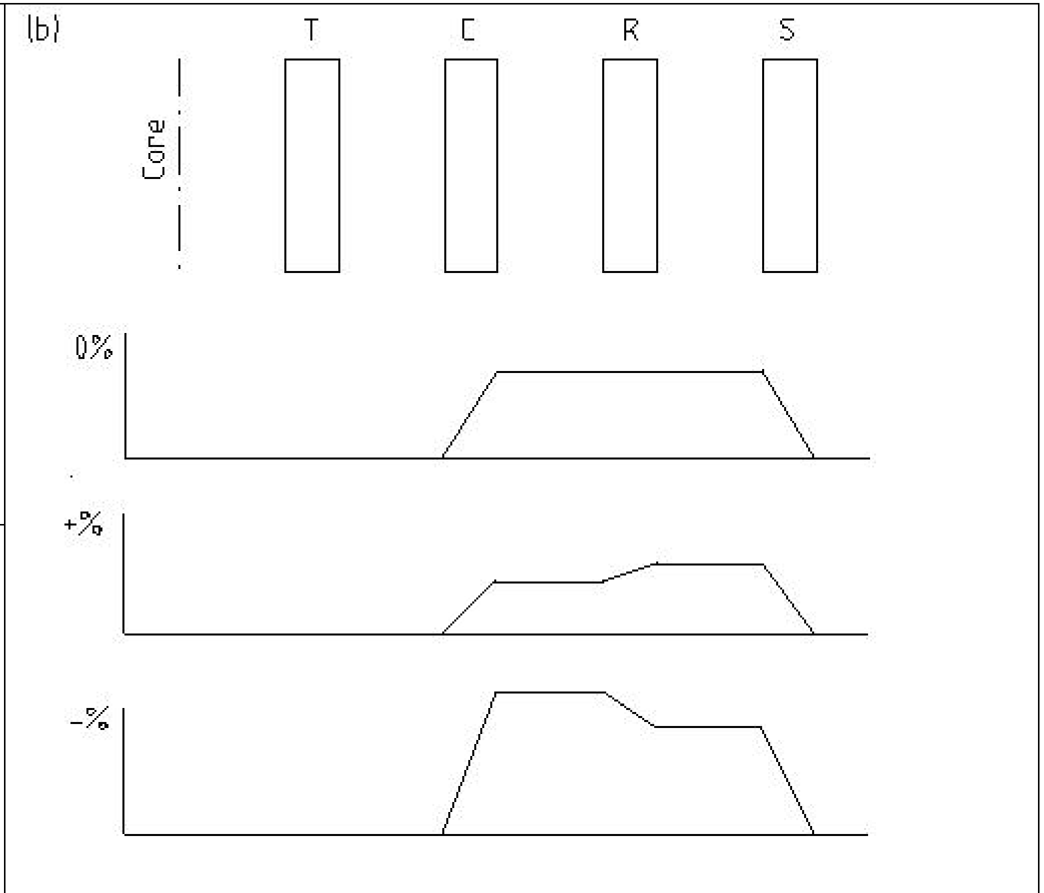


	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	101.7	100	97.22	99.95	100	99.17	92.91	100	107.2
1.5*CS	101.6	100	97.54	99.83	100	99.48	92.82	100	107.5
1.5*SR	102	100	96.86	100.2	100	99.82	93.18	100	106.9

TABLE 23 LV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX RCS

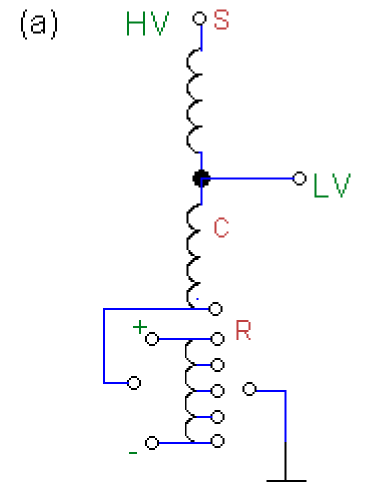


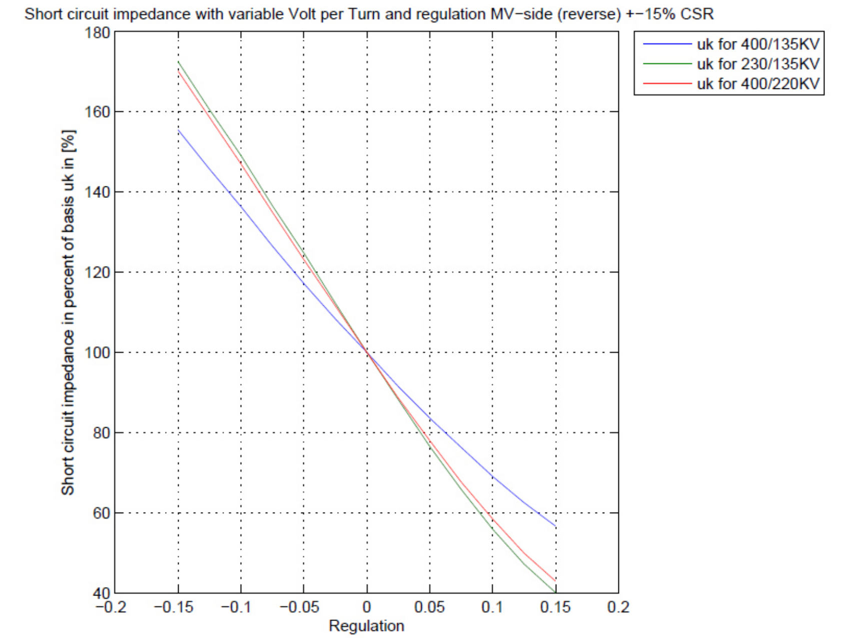


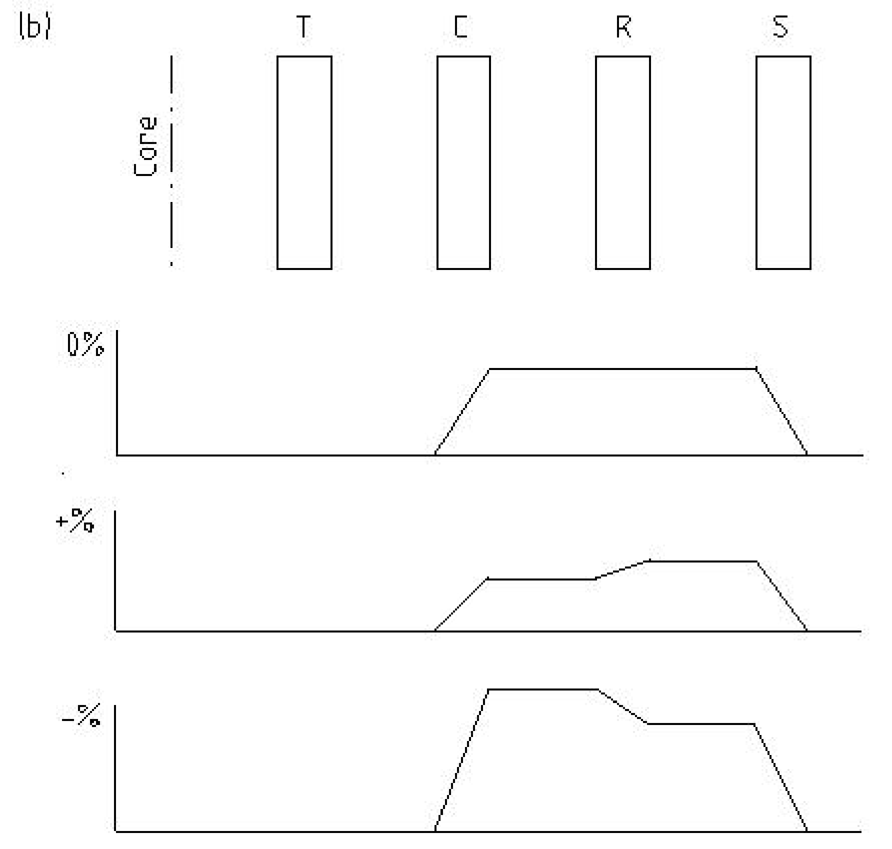


	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	119.6	100	83.18	117.4	100	84.93	109.9	100	91.32
1.5*CS	118.7	100	83.75	116.6	100	85.5	109.1	100	91.91
1.5*SR	20.6	100	82.55	118.4	100	84.3	110.7	100	90.72

TABLE 24 LV-SIDE REGULATION WITH LINEAR TYPE AND CONSTANT FLUX CRS

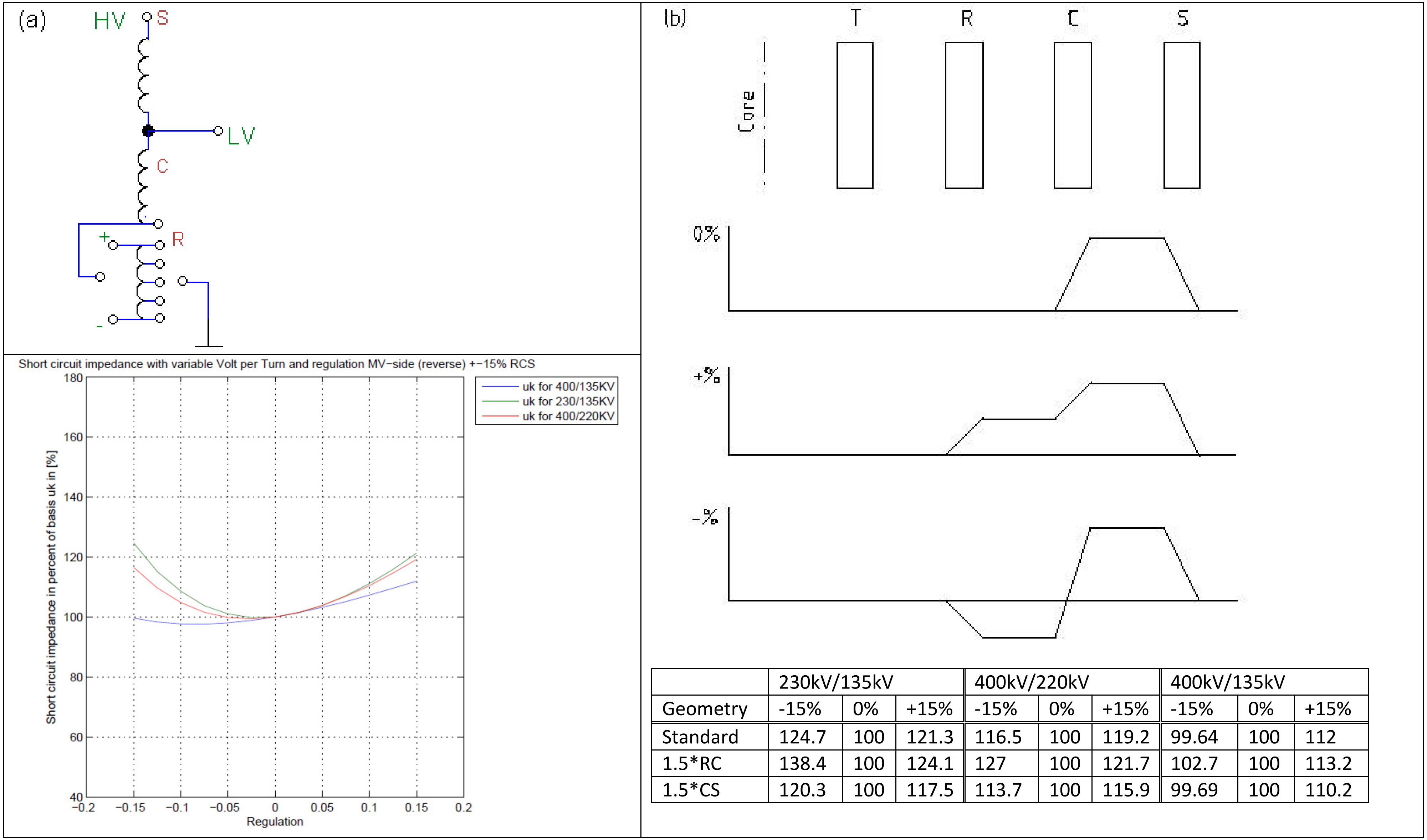






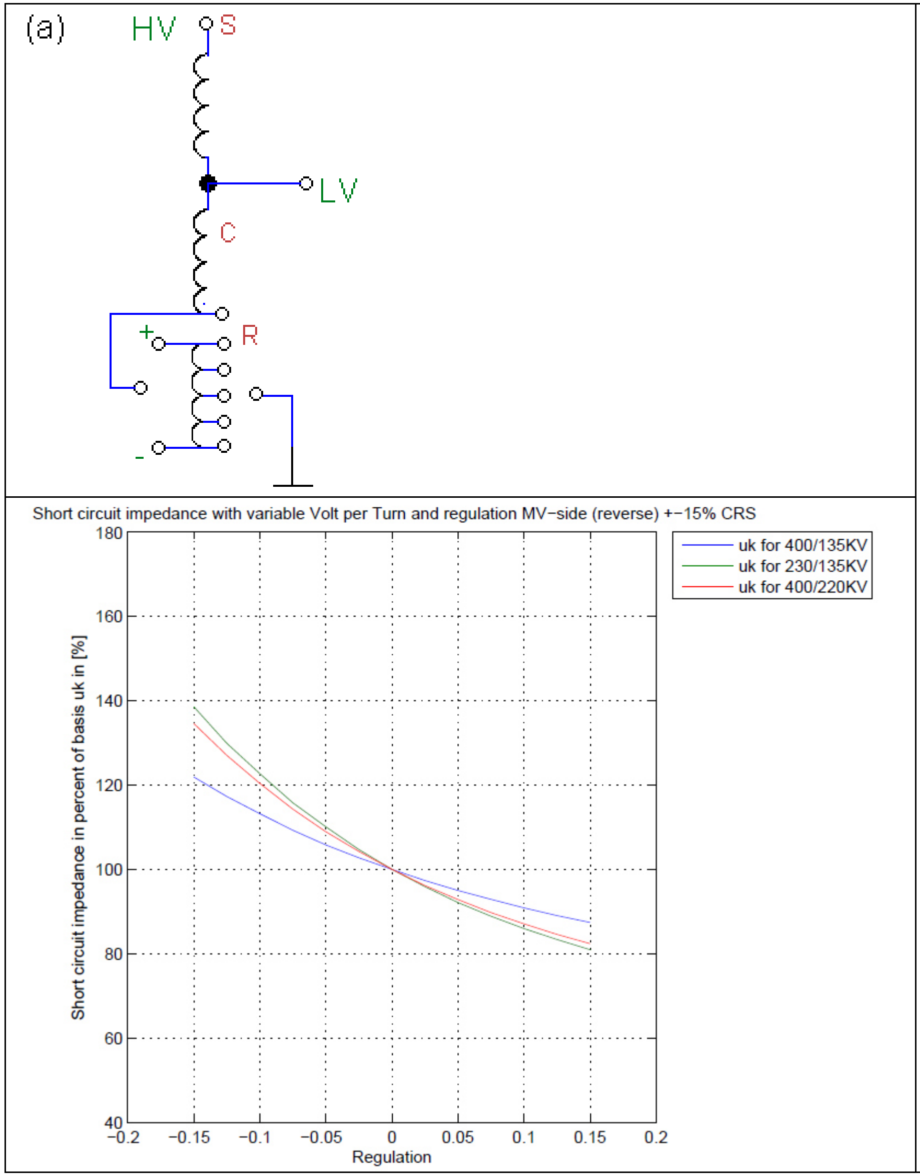
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	172.5	100	40.04	170.2	100	42.9	155.5	100	56.62
1.5*CS	170	100	39.43	167.8	100	42.53	154	100	56.84
1.5*SR	174.9	100	42.52	172.2	100	45.01	156.4	100	57.57

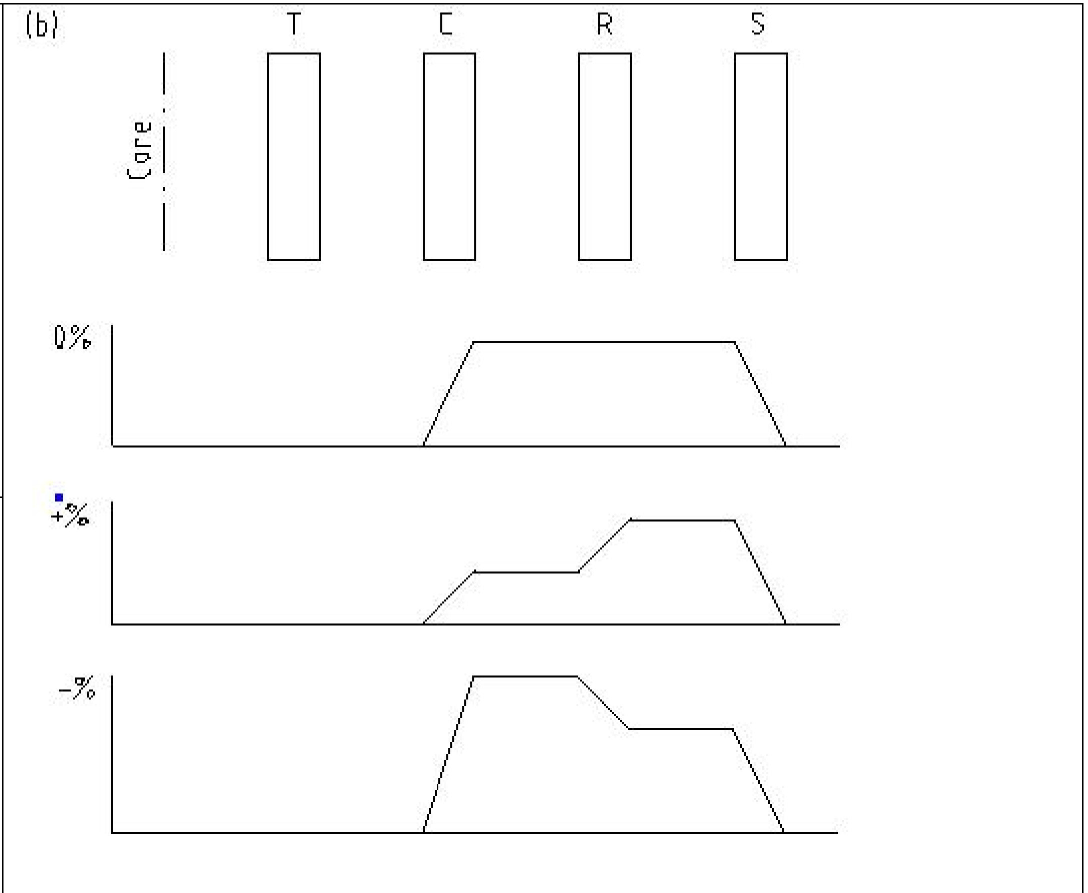
TABLE 25 LV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX CSR



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	124.7	100	121.3	116.5	100	119.2	99.64	100	112
1.5*RC	138.4	100	124.1	127	100	121.7	102.7	100	113.2
1.5*CS	120.3	100	117.5	113.7	100	115.9	99.69	100	110.2

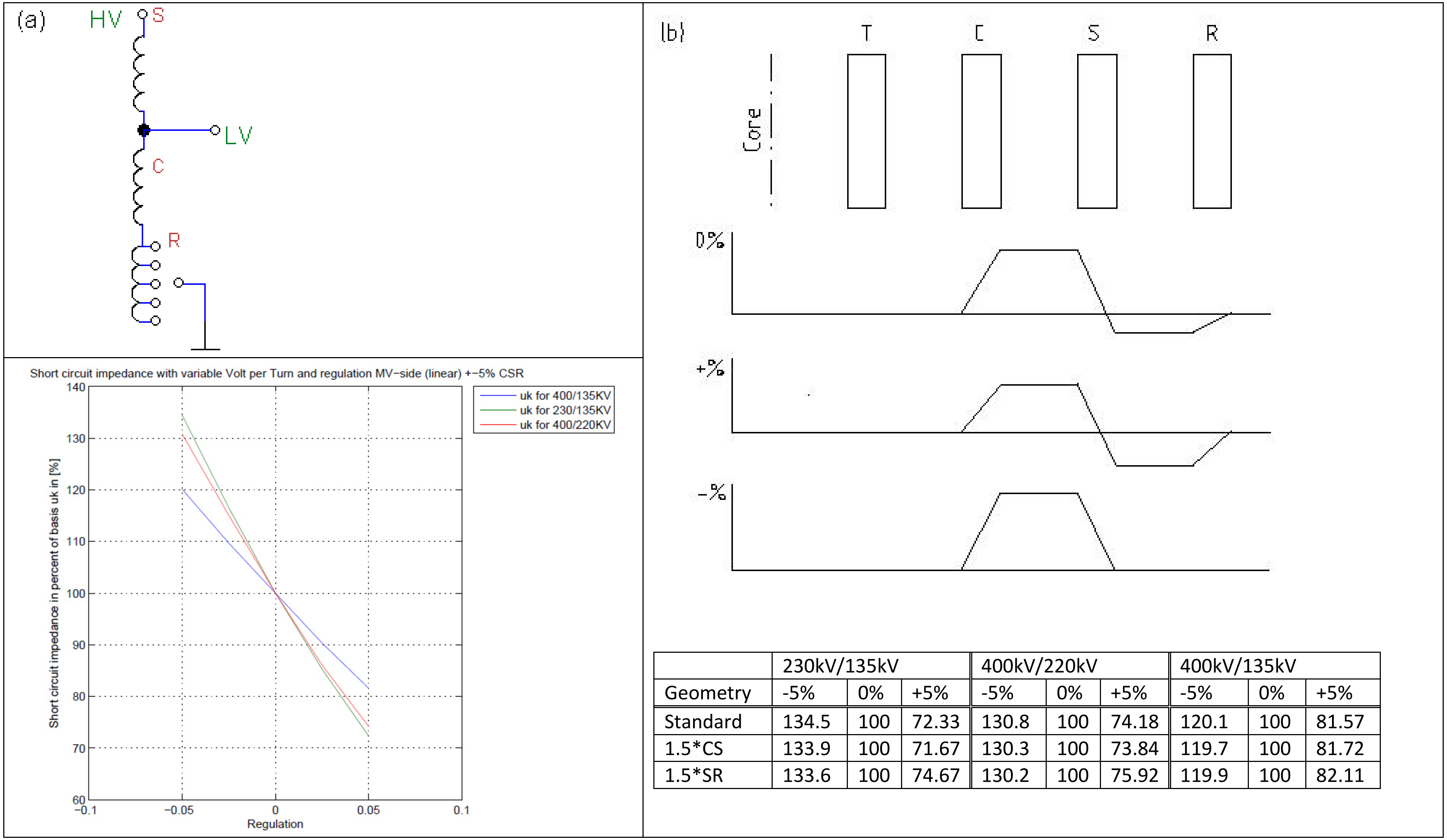
TABLE 26 LV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX RCS





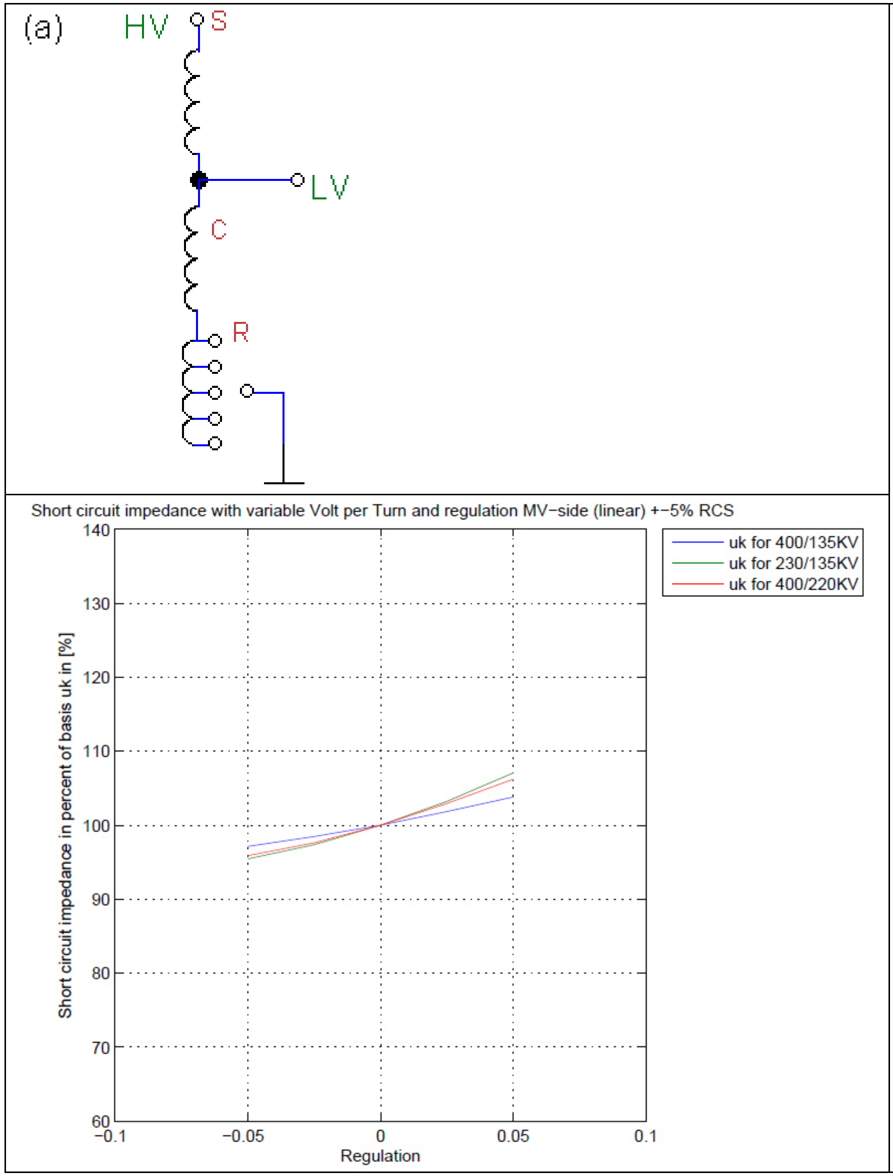
	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-15%	0%	+15%	-15%	0%	+15%	-15%	0%	+15%
Standard	138.6	100	80.95	134.6	100	82.38	121.9	100	87.41
1.5*CR	134.4	100	82.96	130.8	100	84.25	119.6	100	88.74
1.5*RS	143.7	100	78.84	139.1	100	80.45	124.3	100	86.19

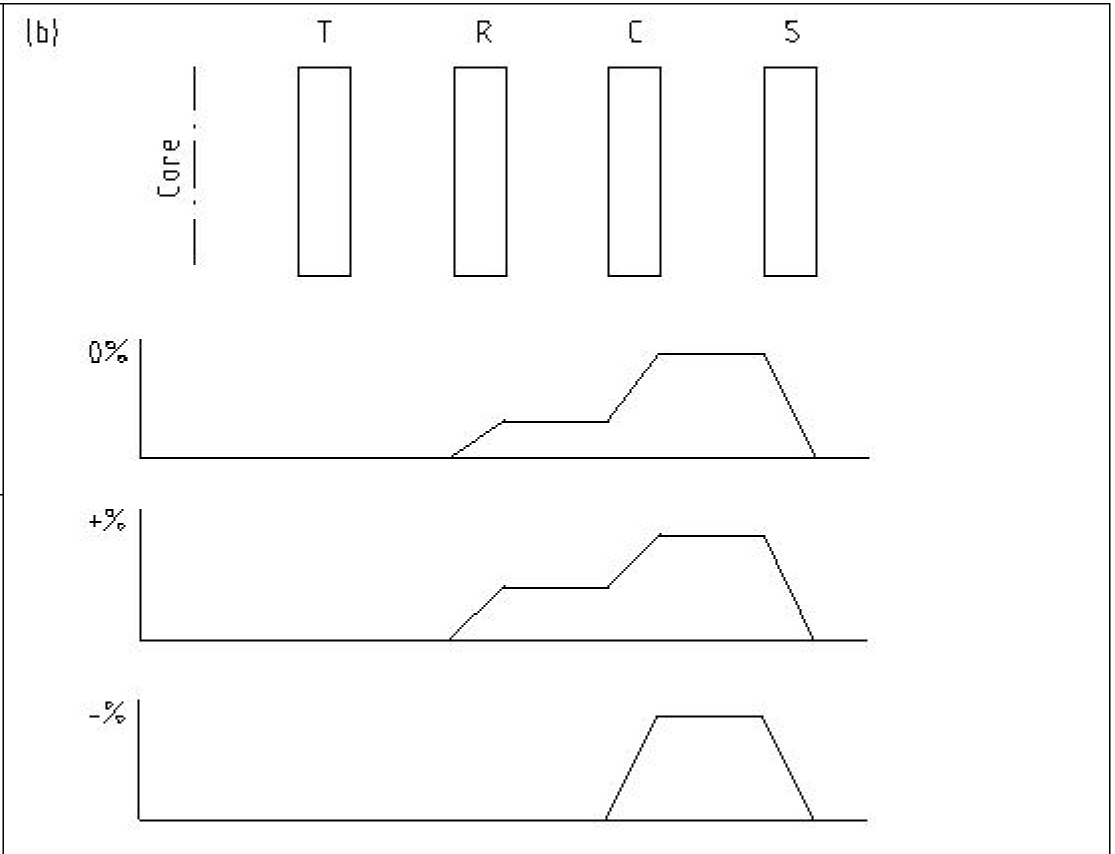
TABLE 27 LV-SIDE REGULATION WITH REVERSE TYPE AND VARIABLE FLUX CRS



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	134.5	100	72.33	130.8	100	74.18	120.1	100	81.57
1.5*CS	133.9	100	71.67	130.3	100	73.84	119.7	100	81.72
1.5*SR	133.6	100	74.67	130.2	100	75.92	119.9	100	82.11

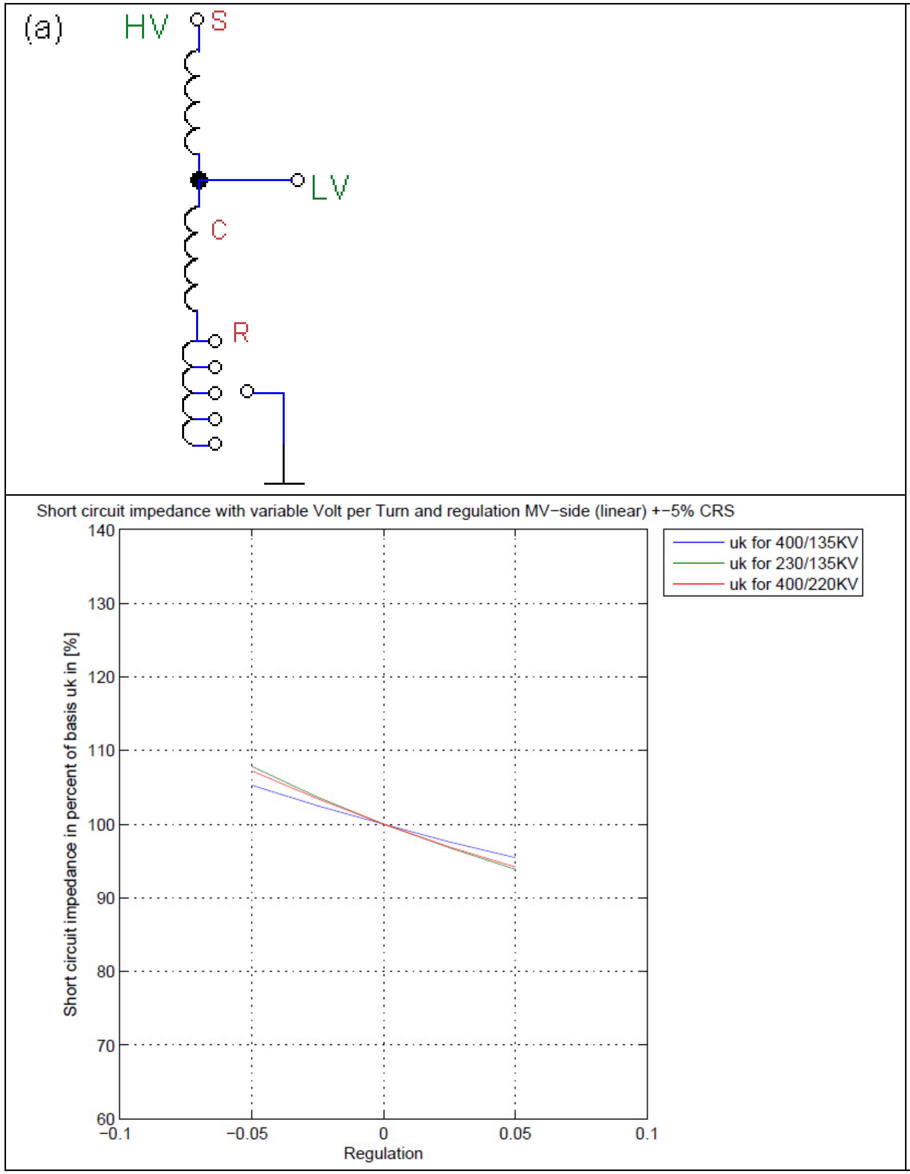
TABLE 28 LV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX CSR

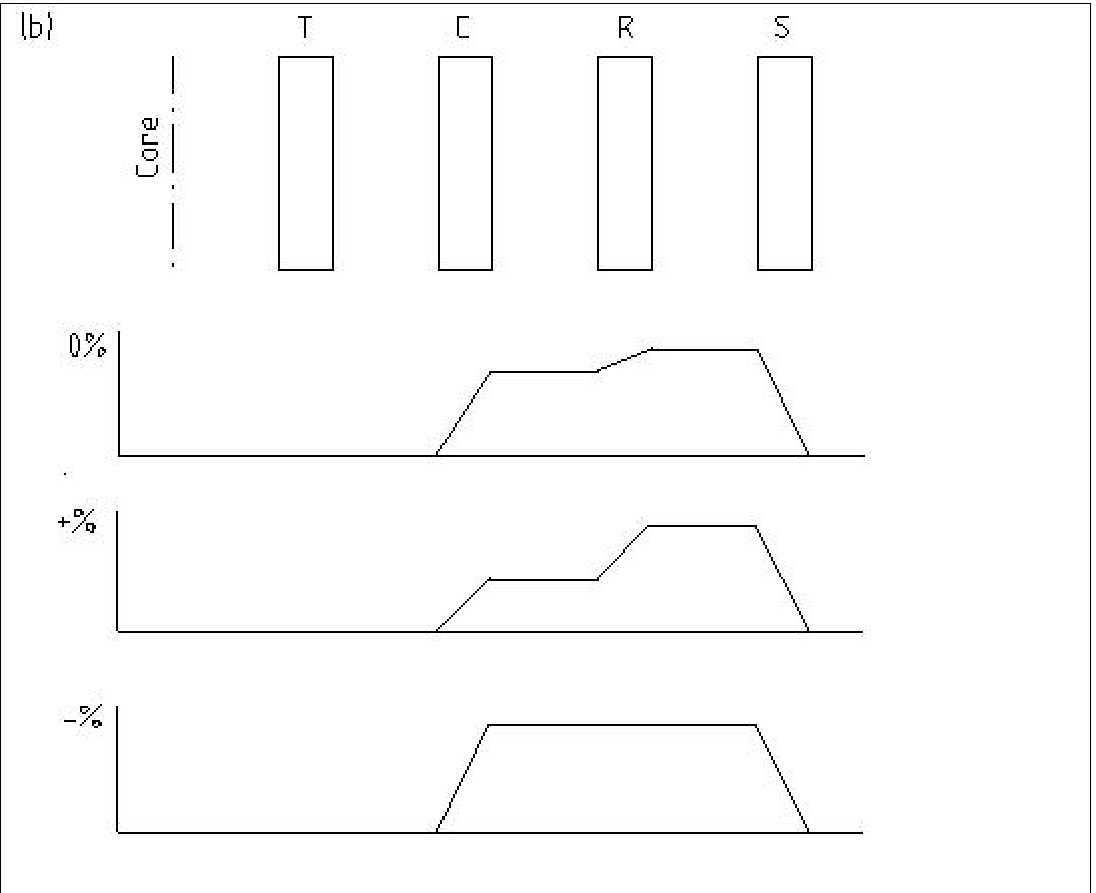




	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	95.44	100	107.1	95.88	100	106.2	97.13	100	103.8
1.5*RC	94.83	100	108.7	95.39	100	107.6	96.94	100	104.4
1.5*CS	96.29	100	105.7	96.62	100	105.1	97.56	100	103.2

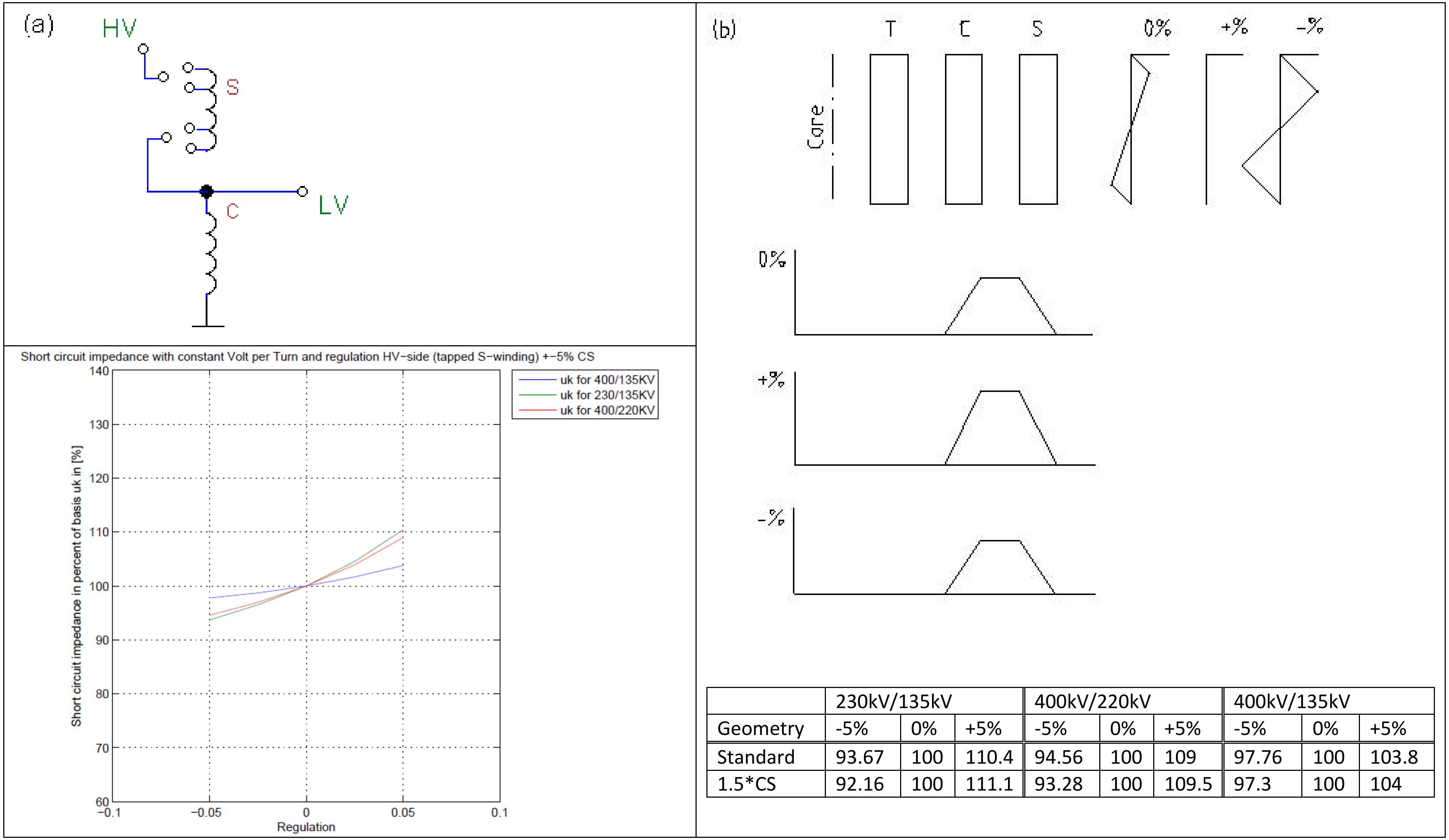
TABLE 29 LV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX RCS





	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	107.8	100	93.85	107.2	100	94.18	105.3	100	95.44
1.5*CR	106.7	100	94.7	106.2	100	94.97	104.6	100	96.01
1.5*RS	108.9	100	93.07	108.2	100	93.46	105.8	100	94.97

TABLE 30 LV-SIDE REGULATION WITH LINEAR TYPE AND VARIABLE FLUX CRS



	230kV/135kV			400kV/220kV			400kV/135kV		
Geometry	-5%	0%	+5%	-5%	0%	+5%	-5%	0%	+5%
Standard	93.67	100	110.4	94.56	100	109	97.76	100	103.8
1.5*CS	92.16	100	111.1	93.28	100	109.5	97.3	100	104

TABLE 31 HV-SIDE REGULATION WITH TAPPED SERIES WINDING AND CONSTANT FLUX CS

For regulation the low voltage side the winding arrangement CRS is not the best choice now the winding arrangement RCS produces the lowest variation of the short circuit impedance over the regulation range. The values for the arrangement CSR are too high and not tolerable so this one is not really used. For some transformer ratios it is possible use arrangement CRS but RCS would be the best solution.

The high voltage regulation problem with the gently gradient for some winding arrangements with a regulation range greater 5% is for low voltage not really visible. A reason could be that for low voltage regulation the value of the factor F_C has not such a big variation over the regulation range.

The transformer ratio has also some influence in the variation of the short circuit impedance. A bigger transformer ratio could give the electrical designer the possibility to use the arrangement CRS too. A smaller transformer ratio is responsible for higher u_k values for the arrangements CSR and CRS. For the arrangement RCS a smaller ratio reduces the variation of u_k. The trends of u_k are similar for reverse or linear regulation which can be explained by looking at the ampere turn diagrams.

Again the tables under the ampere turn diagrams show the influence of different insulation gap widths between the windings. For linear regulation type the influence is not really big but for reverse regulation type it is possible to change the trend within some percentage.

Finally the best results for the short circuit impedance are possible for LV-regulation with the winding arrangement RCS where the regulation winding is the innermost winding of them.

The last table shows a high voltage regulation with a tapped winding instead of an extra tap winding. A tapped winding has the advantage that no extra tap winding is needed but a disadvantage is that over the regulation range a radial component of the magnetic flux exists. Normally this radial component will increase the value of u_k but the radial component is small because tapped windings are used for small regulation ranges to avoid additional problems with short circuit forces and so the height along the regulation range is not really reduced. This and F_C are the reason why u_k has his maximum at the positive tap position where no radial component exists and not as mentioned at the negative tap position. Here a smaller transformer ratio produces higher values for u_k.

At the end to find out which arrangement has the lowest absolute value of u_k for the nominal tap position it is enough to take a look on the arrangement and the formulas. The important factor who answers this question is not an electrical factor it is a geometrical one, it is the mean diameter D_m of the arrangement. The lowest D_m produces the lowest u_k this is arrangement CSR followed by CRS and RCS.

7. Conclusion and Discussion

The thesis gives an overview of the actual technologies for active parts design and shows the calculated trends of u_k over the regulation range for different autotransformer configurations to allow a preselection of possible winding arrangements.

The first part was a short reflection on the actual technologies because it is possible fill pages of pages with informations of the active parts. Maybe there are newer materials available for the design process but at the moment they are too expensive to use them.

The ampere turn diagrams for every winding arrangement is the first step to find out how the trend should look like allows everybody to find out how the trend should look like. To find the maximum values the calculation of u_k is necessary.

In chapter 2.6 it was explained that the insulation between windings is a barrier system and is not a single material to reduce the insulation gap width compared to the value of the calculated width. Therefore the calculated absolute values of u_k are too high compared to real values because a smaller insulation gap reduces the value of u_k. But the main topic was to show the trend of u_k along the regulation range which is only the relation of u_k for different tap positions to them of the nominal tap position. The main insulation gap is the same for all calculations only the auxiliary gap does not exists for all calculations there could be a little error in the calculations but it was shown during the calculations with increasing the insulation gap width to 1.5 times the original width that this error is not very large. Because of the fact that these trends should allow a preselection of possible arrangements and does not show the final values of u_k which are presented to the customer and the allowed tolerances for u_k the calculation should be enough for a preselection.

The maximum and minimum values of the calculated trends are similar to the reference trends[74] sometimes they are a little bit different but one reason could be the different insulation gap. It is not possible to compare the calculated values between the end tap positions and the nominal tap positions with reference values because in the reference trends only values for the end tap positions and the nominal tap position are calculated.

The calculated trend for “HV-side regulation with reverse type and constant flux RCS” looks different compared to the other trends at the negative end tap position because first the trend increases but at the end it starts to decrease. Normally the values should increase from nominal tap position to negative tap position. This effect is visible only for small transformer ratios so the factor F_C could be responsible for it.

The statement which winding arrangement would be the best solution for a given regulation side was made with the point of view that a small variation of the short circuit impedance

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[74] B. Heller, "Methods and means of voltage regulation of large auto transformers
," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2011 8th International Conference On,* 1973, pp. 9-24

along the regulation range is the preferred solution. However of course it depends on the customer requirements which trend is needed and which winding arrangement would fit it.

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9. List of tables

10. List of figures