Cahier Technique N°13
Principe de réduction des courants d’enclenchement des transformateurs

Numerical transformer inrush current minimizer
Principle of the operation

Rev 1.0

PROTECTA HUNGARY

MICROENER

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CONTENTS

1 Introduction

The “inrush current” is a known phenomenon: uncontrolled energizing of a transformer can cause high-magnitude transient current because of the saturation of the iron core. The magnitude of this inrush current is close to that of short-circuit currents, and can cause loss of life or damage to the transformer. The modern protective relays are prepared to deal with the highly distorted current shape, but the power quality is reduced by this effect. This document describes the inrush current phenomenon, and analyses the possibility for controlled switching. Based on proposals of several publications, Protecta realized controlled switching with modern microprocessor-based hardware. The conclusions of the field experiences justify the application of controlled switching to eliminate transformer inrush current. This controller function became part of the standard Protecta protective devices.

2 Energizing a transformer

When a transformer is energized, in many cases high transient current can be measured. This “inrush current” is illustrated in Fig. 2-1, which shows the typical distorted current waveform, and the high peak values.

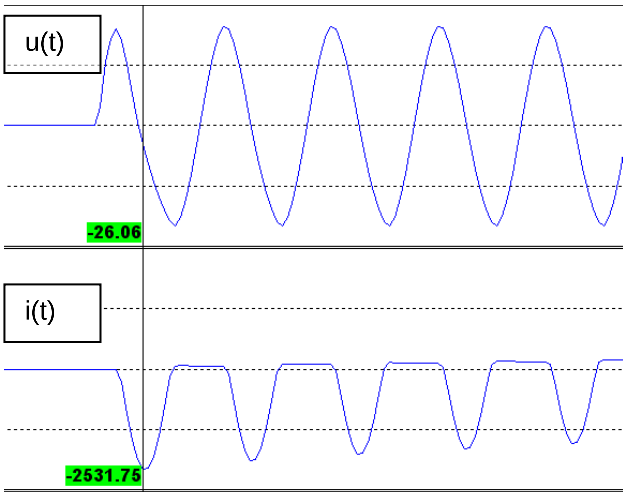

Fig. 2-1 A typical transient when energizing a transformer

This current causes high dynamic forces in the transformer windings, decreases the expected lifetime of the transformer, and can cause damage to the windings as well. The difficulty for the protective devices is that this current flows only on the energized side of the transformer, and the differential protection may trip the transformer at once. The modern protective devices solve this problem by analysis of the special current shape, but because of the high dynamic forces inside the transformer, and because of the effect on the whole network, it is desirable to eliminate these high current peaks.

The analysis of the inrush current first in a single-phase transformer then in a three-phase transformer explains the influencing factors and gives hint to eliminate them with controlled switching.

3 Energizing a single-phase transformer

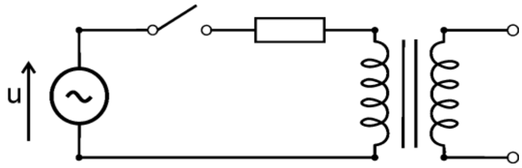

Fig. 3-1*Energising a single-phase transformer*

The relationship between the flux in the iron core *Φ(t)* and the voltage *u(t)* is:

Integrating the voltage, the flux can be calculated, which starts with its residual value *Φe*.

The *Φe*. residual flux remains in the iron core at the end of the preceding disconnection of the transformer.

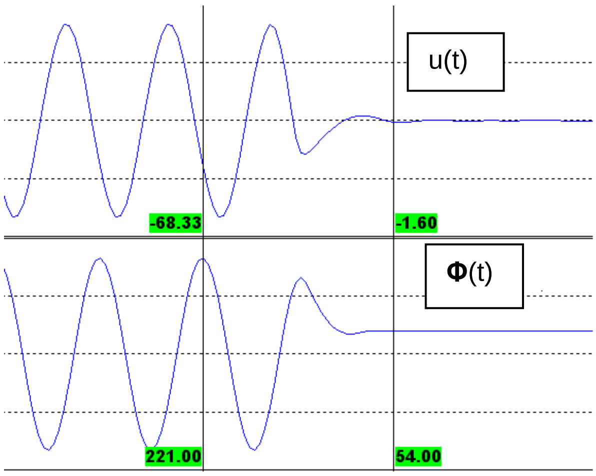

Fig. 3-2 *A typical transient when disconnecting a transformer*

Fig. 3-2 shows a typical voltage waveform registered during the disconnection process, together with the calculated flux-time function.

As Fig. 3-2 shows, that at the moment of opening the circuit breaker the voltage does not drop immediately to zero. This is caused by the inductive energy stored in the winding of the transformer and by the capacitive energy stored in the distributed capacitances of the transformer. The voltage decreases with damping swings; and during that time the flux changes as well. At the end of this process the non-zero residual flux is stored in the iron core. In the next energizing the flux starts from this value.

Fig. 3-3 shows a disconnection with a significant value of residual flux, then an energizing in a random moment. In this case the transient flux value is higher than the saturation flux of the iron core, the consequence of which is the high inrush current.

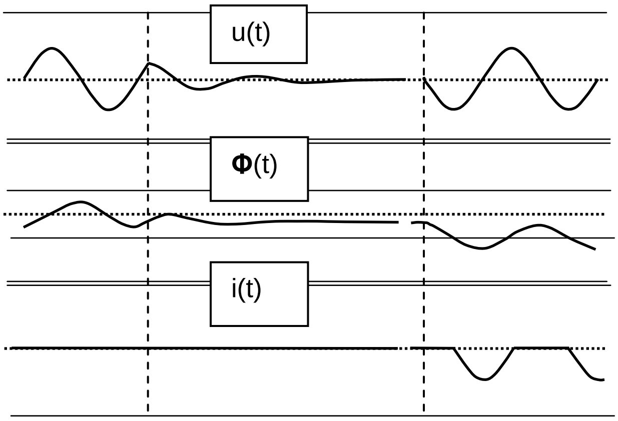

Fig. 3-3*. Energizing in a random moment*

Fig. 3-4 however shows an energizing, which finds the optimal moment, when the residual flux is the same as the momentary value of the prospective sinusoidal flux. If the transient peak value is not higher than the saturation flux value of the iron core, there is no inrush current.

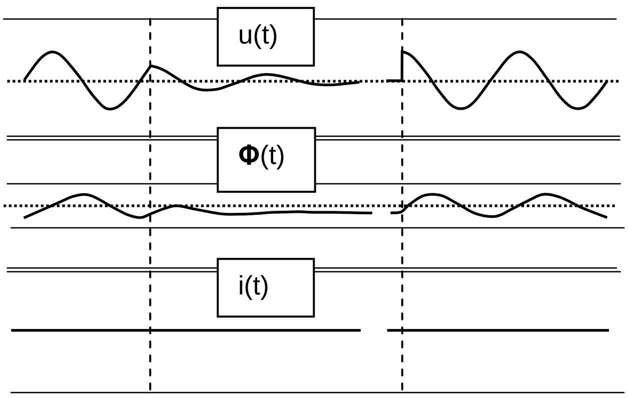

Fig. 3-4 *Energizing in the optimal moment*

Based on Fig. 3-3. and Fig. 3-4. The principle of the controlled switching is to find the moment of energizing, when the residual flux is the same as the momentary value of the sinusoidal steady state flux. This way the inrush current can be eliminated.

4 Inrush current minimization of three-phase transformers

4.1 The applied physical model, approximation

There are several types of three-phase transformers, the number of which is increased by the construction of the iron core and the number and connection groups of the coils.

Concerning the iron cores, the transformer bank can be assembled of three single phase transformers or the iron cores can be joined. In this second case the number of limbs can be three or five. On an iron core limb two or three coils can be located, constructing the primary, secondary and additionally the tertiary voltage levels. The connection of the coils of the individual voltage levels can be grounded or ungrounded Y, delta or zigzag. At energizing, the transient behavior of all these types need individual analysis.

This document analyses firs one of them: the three-limb grounded Y primary and delta secondary transformer, without tertiary voltage level. The energizing is supposed to be performed from the grounded Y side (Fig.1-1. and Fig.1- 2).

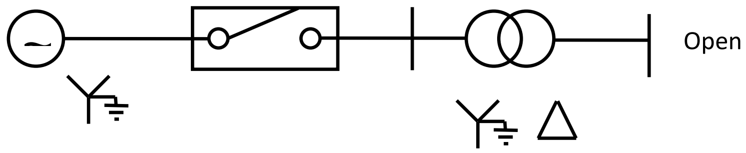

Fig. 4-1 Energizing scheme of a YoD11 transformer

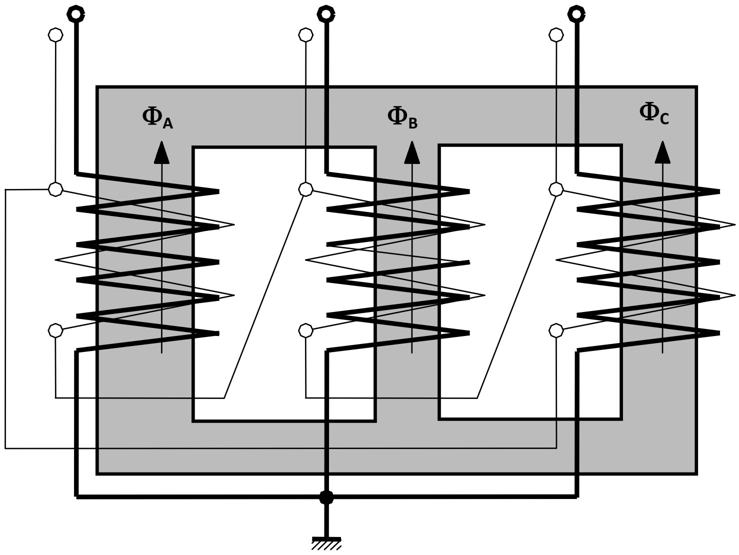

Fig. 4-2 Construction of the analyzed transformer and positive flux direction definition

To analyze the principles the transformer does not need to be modeled with full details. In this description the following simplifications are applied:

- The full symmetry of the transformer is supposed, which means that the deviation between the central phase and of other two phases is neglected (the magnetic resistance of the jokes is supposed to be zero).
- The load on the secondary of the transformer is neglected; all other reactance values except the magnetizing reactance are neglected.
- Our aim is to prevent magnetizing inrush current. This can be achieved by keeping the flux below the saturation, and the means is controlled switching. In this method the moment of closing the poles of the circuit breaker is driven to the optimum. The result of which is that the flux values cannot increase above the saturation value. If this is achieved, then in this range the approximation of the reactance by a single linear value is an acceptable assumption. Of course with this model the maximum peak value cannot be calculated, but our aim is not the calculation of the high peak values but to avoid them. It is obvious however that with increasing the flux the current increases to extreme high values, which depends not only on the transformer but on the reactance of the supplying network too.

4.2 Asymmetrical switching states

At closing or at current interruption, the three poles of the circuit breakers cannot operate at the same moment. In this procedure there are time spans, when temporarily a single phase is connected, and there are time spans when two of them. These states will be analyzed individually.

The flux in case of three limbs transformers – as only the magnetizing reactance is considered – cannot leave the iron core. So in every moment the sum of the three flux values is zero. (The non-zero value is possible only if all three phases are excited, and the sum of the excitation is not zero.) Consequently the basic equation is:

$$\Phi_A + \Phi_B + \Phi_C = 0$$

4.2.1 Single phase connected to the source voltage

The connected phase is the phase „A”, the voltage of which is „forced”. According to the induction low

$$u_A(t) = N\frac{d\Phi_A(t)}{dt}$$

the flux will be:

$$\Phi_A(t) = \Phi_{A0} + \frac{1}{N}\int u_A(t)dt$$

The flux lines are continuous along the iron core limbs of the disconnected phases. As full symmetry was supposed, and the magnetic resistances of all three phases are identical, half of the flux is in the limb “B”, the other half is in the limb “C”. The direction of them, according to the positive directions of Fig. 4-2 is opposite:

$$\Phi_B(t) = \Phi_C(t) = -\frac{\Phi_A(t)}{2}$$

Accordingly the induced voltages in phases „B” and „C” is identical, half of the voltage connected to phase “A”, the directions are opposite:

$$u_B(t) = u_C(t) = -\frac{u_A(t)}{2}$$

Remark: as the sum of all three phases is zero, the sum of the voltages in the secondary delta is zero too; no current is induced in the secondary delta connected windings. The effect of the secondary windings to the flux need not be considered.

4.2.2 Two phases connected to the source voltage

The connected phases are supposed to be phase „A” and phase „B”, the sinusoidal voltage of which is „forced”. According to the induction low:

$$u_A(t) = N\frac{d\Phi_A(t)}{dt}$$

$$u_B(t) = N\frac{d\Phi_B(t)}{dt}$$

Consequently the fluxes in the limbs are :

$$\Phi_A(t) = \Phi_{A0} + \frac{1}{N}\int u_A(t)dt$$

$$\Phi_B(t) = \Phi_{B0} + \frac{1}{N}\int u_B(t)dt$$

The flux lines can close along the iron core of the unconnected phase “C”, so the flux there will be the sum of the fluxes of the connected phases, the direction is opposite to the positive direction according to Fig. 4-2. As the voltages are phase voltages of a symmetrical voltage system:

$$-\Phi_C(t) = \Phi_A(t) + \Phi_B(t) = \Phi_{A0} + \Phi_{B0} + \frac{1}{N}\int \left(u_A(t) + u_B(t)\right)dt$$

The voltage induced in phase „C”:

$$u_C(t) = N\frac{d\Phi_C(t)}{dt} = -\left(u_A(t) + u_B(t)\right)$$

The voltage of the un-energized phase „C” is the same voltage as it would be in full energized state.

In the analysis below the statements above will be applied.

Remark: as in every moment the sum of the three voltages is zero, the sum of the induced voltages in the secondary coils will be zero too, consequently no current in the closed loop will flow (no zero sequence current component). The conclusion is that the delta winding has no influence on the flux distribution.

4.3 Evaluation of special switching sequences

In this chapter some special sequences among the infinite variations will be selected, and the final general conclusions will be stated based on these special switching processes.

4.3.1 Optimal switching off to result zero residual flux values

In a steady state energized operation, when the flux time-function do not include DC component, then both the flux vectors and the voltage vectors result symmetrical systems, 120 degrees are apart from each other, and the flux vectors are delayed by 90 degrees as compared to the referring voltage vectors. In this case let's switch off phases "B" and "C" at the same moment, when the voltage in phase "A" is at the positive zero crossing state. Define this moment to be t=0. (See Fig. 4-3.) At that moment the flux at phase "A" is at its negative peak value, the flux in the other two phases are at half value, and opposite polarity to flux in phase "A".

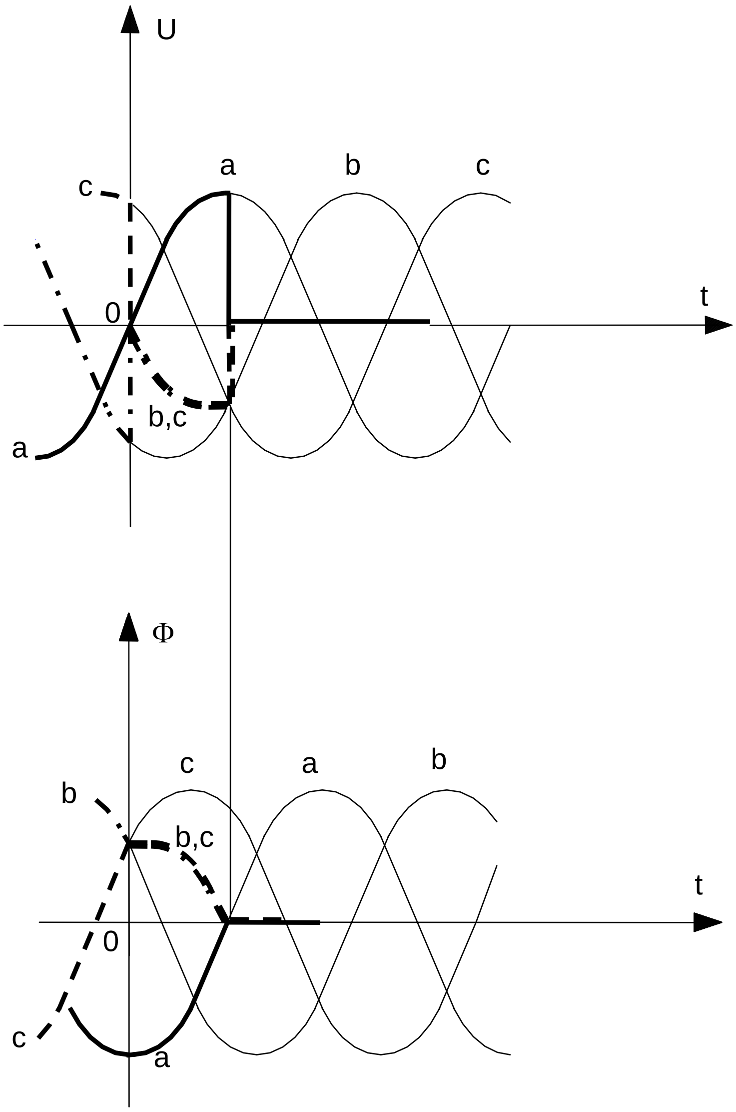

Fig. 4-3 Optimal witching off sequence to result zero residual flux

Accordingly after that moment only phase „A" remains energized, and the voltage momentary values in phases „B" and „C" will be the opposite half value of that of phase „A". This behavior is explained in chapter „*1.2.1 Single phase connected to the source voltage*".

After a quarter of period the integral of the positive „A" phase momentary values will change the flux to zero value in phase „A". During the same time the flux values in phases „B" and „C" will change starting at the positive half value to zero value too. Consequently if phase „A" is switched off at 5 ms (a quarter of period) then the result will be zero flux value in all three phases.

Except the cyclically symmetrical states and the state of opposite polarity, this is the only switching sequence, which will result zero residual flux. After all other switching off sequences the residual flux will differ from zero at least in two, but usually in all three phases. It is well known that the moment of switching off the AC currents happens normally at current zero crossings (otherwise the interrupted inductive energy will result current and voltage swings as the interaction with the internal capacitances of the transformer). The consequence is that in practical cases the residual flux will differ from zero.

Related to the conclusions above there are three more facts the attention shall be drawn to them:

1. When the phases „B" and „C" are switched off at Voltage "A" zero crossing, their current crosses zero only with special load condition the zero at the defined moment. Consequently in general case the current should be chopped. This would be not the natural moment of disconnection. So the possibility to select this sequence is low (disconnection of pure reactive current).
2. The analysis above neglects the hysteresis loop of the magnetizing curve of the iron core. The effect of the loop is that at current zero crossing the flux is not zero, so the natural moment of zero crossing always result residual flux, which is not zero. This shows too that achieving zero residual flux with a simple disconnection is practically not possible.
3. The analysis above neglects the distributed capacitances of the transformer and those of other elements connected to the transformer. The effect of these capacitances is as follows: when the current on an inductance is not zero, then it stores inductive energy. If the disconnection "chops" the current, then this inductive energy is transferred to the capacitances, changing to capacitive energy. The result is a swinging process, which decays according to the internal damping. These swings can be detected in the voltage waveforms. This can influence the residual flux values in the transformer.

4.3.2 Optimal energizing, starting at zero residual flux

Supposing zero residual flux (as the result of special disconnection described in section 4.3.1), now switch on first phase "A" at voltage peak value. (See Fig. 4-4.) In this case phase "A" starts with the steady state flux, no overflux is expected. In the phases „B" and „C" however the flux starts to change immediately as the consequence of the induced $-u_A/2$ voltage, and they start to increase in negative direction. After 5 ms they reach half value of the steady state flux peak, which is the momentary value of the steady state flux at that moment. If one of these two phases is energized at this moment, there will be no transient in the flux, the steady state is settled. (The switching of the third phase can be any time after that moment, the delay has no influence. They can be switched simultaneously).

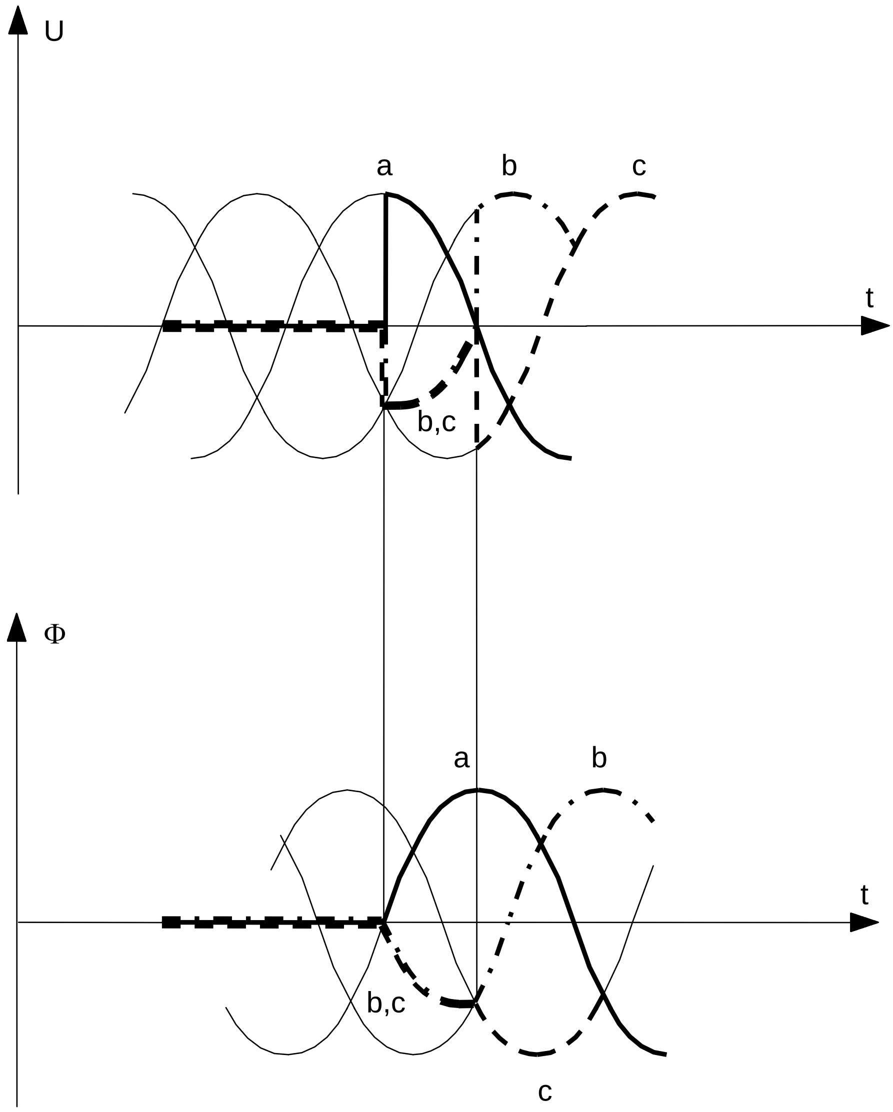

Fig. 4-4 *Optimal energizing after zero residual flux*

Except the cyclically symmetrical states and the state of opposite polarity, this is the only switching sequence, which will result no transient overflux starting at zero residual flux. The consequence of all other switching sequences is overflux at least in two, but mostly in all three phases, the result of which is high inrush current peak value.

It is obvious, that if the residual flux in one of the phases is not zero, then this switching sequence will result overflux and high inrush current peaks.

4.3.3 The most unfavorable residual flux values

In a steady energized state, when the flux does not contain DC component and both the fluxes and the voltages form symmetrical systems and the time delay between the voltages and the related fluxes is 90 degrees – switch off first phase „B”. The moment of switching off has no influence, since the remaining two energized phases keep the symmetrical state. (See Fig. 4-5 .)

Switch off now as the second phase „A” 150 degrees after zero crossing (8.3333 ms) (this is the moment of identical momentary values of phase „A” and „B”, the voltages are half of the peak value. After that only phase „C” is energized, the momentary value at the switching is the peak value. The result is that the voltage in phase “A” does not jump; the value is continuously half of that of the normal phase value. It needs additional 5 ms (a quarter period) to reach zero. As Fig. 4-5 shows, the area of the voltage curve is extended with the shaded area. The consequence is that the flux, as the integral of the voltage increases by about 36.6 % above the peak value. If in this moment (13.3333 ms after the zero crossing) the voltage is switched off in this phase too, this value is kept as residual flux.

It must be pointed out that this extreme value has a very few reality, this 136.6 % high values cannot be expected. The explanation is that the asymmetrical saturation of the iron core limbs will change the magnetic resistance of the sections. As a consequence the flux distribution will be different from that of the symmetrical state. The residual flux is influenced by the hysteresis losses, and the capacitive transients can decrees the residual flux values too.

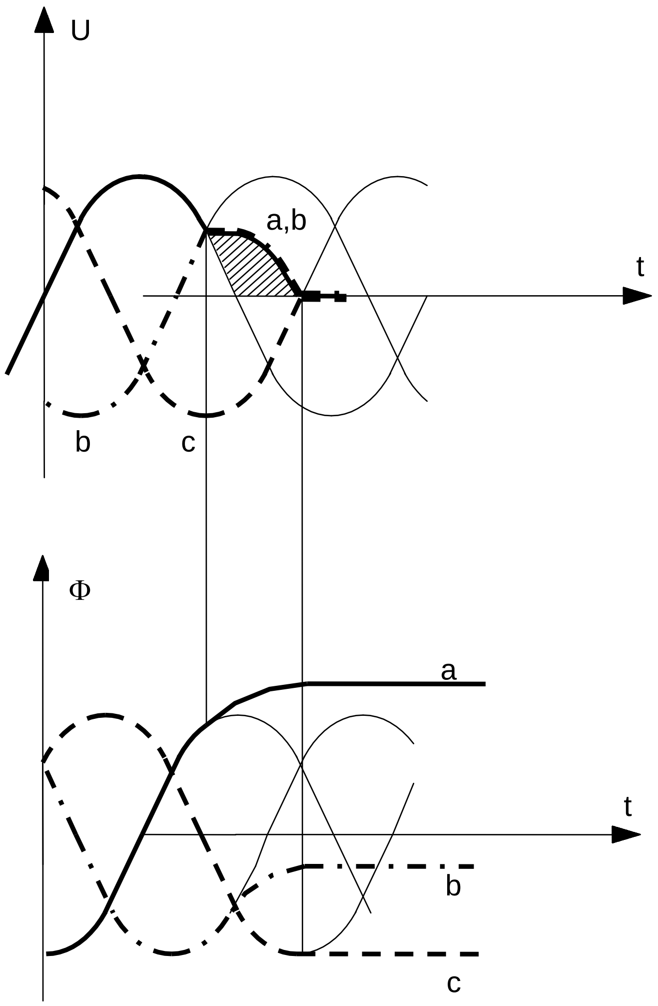

Fig. 4-5. The theoretically highest value of the residual flux

4.3.4 Extremely high flux values

Suppose an extremely high value of the residual flux, as it is described in section 1.3.3. Switch on first phase “B” at its negative zero crossing value. (This means–3.3333 ms, taken phase “A” as reference.) At this moment the half value of voltage „A” is induced with opposite, means positive polarity, and the flux starts increasing. Switch on now phase „A” when the voltage is increasing, and the value is the half of the steady state peak value. (This means the moment +1.6666 ms, related to the positive zero crossing.) With this timing will result the largest voltage-tome area in phase “A”. If the polarity of the residual flux is the same, then the flux peak value is the highest, and the peak value is 2.3666-times of the normal peak value. If the residual flux, as it was calculated before is 1.3666, then with adding this value, the highest peak will be 3.7333-timer rated peak value. This can result the theoretically highest inrush current peak.

It must be pointed out that this extreme value has a very few reality. The explanation is that the asymmetrical saturation of the iron core limbs will change the magnetic resistance of the sections. As a consequence the flux distribution will be different from that of the symmetrical state. The residual flux is influenced by the hysteresis losses, and the capacitive transients can decrees the residual flux values too. Additionally the voltage drop on the network impedance will decrease the voltage of the transformer, and the values of the flux and the current peak values as well.

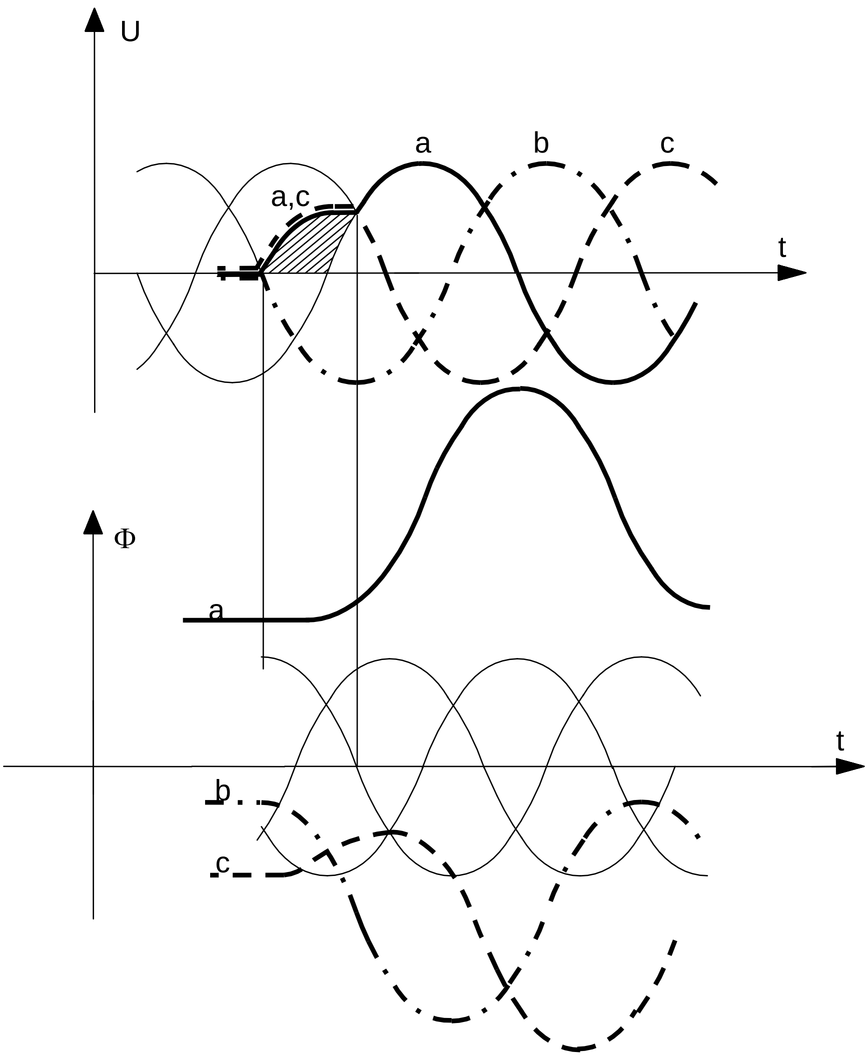

Fig. 4-6 Extremely high flux values

4.4 Switching strategy

The „general" residual flux distribution means however that the sum of the three phase flux values result zero. Accordingly only two phase flux values can be considered to be independent, and can be varied freely.

The fact is that the phase switched as the third one has no influence on the phenomena. Accordingly the switching sequence and switching moments of only two phases need to be calculated.

4.4.1 Switching with circuit breakers driven independently in three phases

When energizing the transformer, the maximal freedom means independent drives in the phases, and the sequence and moment of switching can be selected freely. In this case starting with any combination of the residual flux values, a sequence and timing can be achieved, which cannot result high flux values, and no high current peaks of the inrush current will be generated.

To define the optimal switching the following must be considered:

When the first phase is energized, then the voltage of this phase is "forced" (supposing switching on the grounded Y side). The flux in this phase, starting with the residual value, is the integral of the sinusoidal voltage. The moment of switching in this phase must be selected so that the residual flux value shall be the momentary values of the stationary sinusoidal flux. The solution for the switching phase angle is intersection of the sinusoid and a constant value.

When the first phase is energized, then the flux in the other two phases starts to change too, because there a voltage is induced, the value of which is half of the switched voltage, and the polarity is inverse. The flux starts with the residual flux, and follows the integral of this half voltage. This –generally – shifted sinusoid flux of half magnitude will intersect the stationary flux, which is a sinusoid, and it is symmetrical to the time axis. If the second phase is switched on in one of the intersection points, then the flux in this phase will continue according to the stationary value. No high inrush peak is generated.

The third phase after that can be switched in any moment. The sum of the three flux values is in any moment zero. When a single phase energized state means u, $-u/2$, $-u/2$ voltage distribution, so after one switching the sum remains zero too. If the second phase is switched on, the result will be the symmetrical state, the sum remains zero too. The third phase can be switched in any moment. The reverse sequence of disconnection will result the starting state, the sum of the residual flux remains zero.

When energizing, the moment of the first switching is easy to be defined: in the switched phase the residual flux shall be continued as a steady state sinusoid. The freedom here is to select the phase to be switched first. There are several aspects of selection. Principally the best choice is to select the phase with the highest value of the residual flux. It can assure that no overflux occurs in the selected phase. The disadvantage of this selection is that all three phases must be compared continuously. (It is sufficient to calculate the flux of two phases; the third one can be calculated easily with the assumption that the sum of the three fluxes shall be zero.)

The other possibility to select the phase to be switched first is a fix selection: e.g. phase "A" or the phase of the central coil. The result will be similarly correct. In the following discussion the selected central phase shall be named as "A".

The phase for second switching and the moment of switching needs serious considerations. In one possible strategy select always phase “B”. Here, considering the residual flux alone is not sufficient, because energizing the first phase induces voltage and changes the flux continuously in all other coils, which are not switched yet. The time function can be calculated, and assuming the steady state, symmetrical flux time-function the intersection points can be calculated too. This will be the required moment of switching. Dividing the full flux range into several sections, the pre-calculated moments can be stored in tables. The optimal moment for switching is a simple selection based on the stored residual flux values.

As the calculation time step is 1 ms (18 degrees), the simplest table contains 10 rows and 10 columns. And the residual flux values can principally point to any element of this table. In this table „1” means the 18 degrees range of the negative peak value (and below), and „10” means the flux values in the 18 degrees range of the positive peak value. All other values point to the internal elements of the table, which store the optimal moment for switching, related to the positive zero crossing of the voltage in phase “A”.

There are empty elements in the table, which are impossible combination. E.g., it is not possible that two residual flux values are near to the negative peak, because in this case the residual flux value in the third phase should be high above the positive peak (the sum of the three flux values is zero).

The second phase to be switched is driven according to the values stored in the table, the switching of the third phase after that cannot influence the flux values. With this control the flux will not be high above the normal peak value, and the inrush current peaks are limited to small values.

Table 4-1 indicates the maximal flux values using the switching strategy as it is outlined above. The values are expressed as percent of the rated peak values. It is obvious that in case of correct control the values remain in the small range above 100 %.

B A	1	2	3	4	5	6	7	8	9	10
1					**118**	110	110	110	110	**126**
2					**118**	110	110	110	110	**118**
3				110	110	110	110	110	110	**126**
4		**126**	110	110	110	110	110	110	**118**	**142**
5		**118**	110	110	110	110	110	110	**126**	**142**
6		102	102	110	110	110	110	**126**	**126**	**150**
7		110	110	110	110	110	110	**134**	**150**	**165**
8	102	110	110	110	110	110	**118**	**150**		
9	**118**	110	110	110	110	**126**	**126**			
10	**134**	**118**	**150**	**150**	**150**					

Table 4-1. Highest flux values using individually controlled circuit breaker drives in phase sequence A, B, C

In table 4-1 it can be seen that generally the flux does not overshot more than 10 % , so no high peak values of the inrush current can be expected. Here the minimal overshot is caused by the 1 ms time resolution, so the command is generated with this time error.

In the table the flux overshot is sometimes above 10%, (These are indicated by bold figures.), meaning that the residual flux is near the theoretical steady state peak value (or above it). The reality is however that the swings of the inductive-capacitive elements do not allow these high values. The fix A-B-C switching sequence, according to table 4-1 can effectively limit the inrush current peak values. The advantage of the fix sequence is, that the reference phase is always phase „A”, and only the phase „A” voltage must be continuously checked for the time reference among the supply side voltages, and only the phase „A” and „B” voltages must be integrated continuously to get the residual flux values.

The switching process is relatively sensitive on accuracy of the circuit breaker operating time. The switching command shall be given this time before the optimum, and if there is some additional delay inaccuracy, then the timing will be wrong. In Table 4-2 the element (row 6, column 6) of table 4-1 has been selected to investigate sensitivity. The columns and rows of Table 1-2 shows the effect of inaccuracy of switching phase “A” and phase “B” in milliseconds, the table elements display the highest flux values relative to the rated peak value in percent.

∆B ∆A	-3	-2	-1	0	1	2	3	4
-4	244	221	205	205	205	205	205	213
-3	229	213	181	181	181	181	197	213
-2	221	197	173	157	157	165	181	189
-1	205	181	157	126	126	150	165	173
0	181	165	142	**110**	110	134	150	157
1	205	181	157	126	126	150	165	173
2	213	197	165	157	157	165	181	189
3	213	205	181	173	173	173	189	197
4	213	205	181	181	181	181	181	197

Table 4-2. Effect of circuit breaker operating time inaccuracy in case of individual drives in the phases

Checking the percent values of Table 4-2 it can be seen that the flux at 0-0 point has a minimum value (110 %). The theoretical minimum value is 100 %, the table considers 1 ms sampling time, as the basic inaccuracy. It is obvious that 5 millisecond additional time delay or -5 ms switching in advance finds zero crossing instead of peak value of the supplying voltage. Table 4-2 reflects this tendency too. In case of 2 ms deviations the flux values are relatively high (up to 173 %) which drives the iron core deep into saturation, resulting high inrush current. Taking the possible ±2 ms time deviation, the controlled switching can guarantee that the flux peak cannot reach extremely high saturation (above 200%), so the current peak is not higher than the normal peak current.

Based on the investigations above it is obvious that the best strategy for controlled switching is to search for the highest residual flux value, and first this phase is to be energized to limit the flux to the normal values. If this phase is considered to be the reference phase, then the second switched phase shall be timed according to the time delay values stored in the program. The switching moment of the third phase does not influence the flux values. This strategy, using circuit breakers with individual drives for the phases can guarantee the flux values below 110% of the rated flux peak, and can effectively prevent high inrush currents.

Remark: concerning the peak values of the inrush current, no exact value can be predicted. To calculate the value the source impedance, the full magnetizing curve of the iron core, the exact construction of the iron core, the structure of the coils etc. must be known. It is obvious however that if the flux value is limited to values not too high above the saturation value, then the inrush current is limited below the rated current peak value too.

4.4.2 Switching with circuit breakers of common drives for the phases

In common drives for the circuit breaker phases the individual contacts can be mechanically delayed relatively to the other phases. This time delay can result optimal switching for capacitor banks for example, where the discharged state before energizing can be supposed. The aim in this case is to avoid sudden jump in the voltage and prevent high charging currents and prevent swings as the interaction with inductive elements of the network. For this purpose the grounded neutral capacitor banks are energized near the voltage zero crossing in individual phases. As the time of voltage zero crossing is fix in phase sequence A-B-C as 0 – 6.6666 – 3.3333 ms then the strategy is as follows: Control the drive considering phase “A” to the own zero crossing of the voltage, then the other two phases can follow each other in the given sequence and with the mechanically defined time delay.

If the neutral point of the capacitor bank is isolated, then the first pole does not close any circuit and the second one switches line-to line voltage on two phases of the capacitor bank. So the first two phases are switched at the same time, when the related line-to-line voltage is zero, (the momentary values of the phase voltages are identical). In this case, the not switched phase voltage changes according to –1/2U of the prospective voltage. The momentary value of this voltage can be identical with the phase voltage only if the value is zero. So the ideal mechanical time delay is 0-0-5 ms, where time equals to zero at zero crossing of the line-to-line voltage.

For shunt inductances, having iron cores individually for each phases are usually switched with circuit breakers of mechanically delayed common drives. In this case the phase sequence is A-B-C with mechanical time delay of 0-6.6666-3.3333 ms. In this case the t=0 moment is at the peak voltage of phase „A” and this method drives the other two phases to their own voltage peak values. The steady state flux in these moments is zero in the individual phases (90 degrees delay relative to the voltages). Remark: the inrush current will be eliminated only if the residual flux in the phases is zero too. If not, then it is better to drive the phases of the circuit breaker individually, according to the measured residual flux values.

4.4.2.1 Switching with 5-0-5 ms delayed common drives

Section 4.3.2 analyses switching in case of zero residual flux in all three phases. The result was that the central phase was switched at voltage peak value, the other two phases with 5 ms time delay. The switching timing to the peak voltage of the central phase is 5-0-5 ms. Based on the analysis as described above it is obvious that in case of other residual flux distribution this strategy cannot result optimal switching.

The solution for general residual flux distribution can be the result of optimization only, which can be near the optimum in most cases. The inrush current cannot be fully eliminated, but can be kept within reasonable limits. The control procedure can guarantee the elimination of the highest inrush current peaks only.

Returning to the three-phase Y_od type transformer with three-limbs iron core, and suppose zero residual flux in all the limbs. This state was analyzed in Fig. 4-3. The conclusion was that switching phase “A” at voltage peak shall be followed switching the other two phases „B” and „C” together with 5 ms time delay. So the required switching sequence was 5-0-5 ms.

In all other flux distribution the first phase shall be switched not at voltage peak but sooner or somewhat later, and the subsequent two phases shall be switched not with 5, but after 1 to 9 ms time delay. Accordingly if the phase delay is mechanically fixed to 5-0-5- ms, then the optimal switching cannot be performed, but with optimization the flux peak and so the inrush current peak can be minimized.

If the minimization procedure is performed off-line, scanning all real residual flux combinations, then the required switching moments can be stored in a separate table. The algorithm will then control the switching according to the stored values.

Remark: concerning the peak values of the inrush current, no exact value can be predicted. To calculate the value the source impedance, the full magnetizing curve of the iron core, the exact construction of the iron core, the structure of the coils etc. must be known. It is obvious however that if the flux value is limited to values not too high above the saturation value, then the inrush current is limited below the rated current peak value too.

The headlines of Table 4-3 sow the residual flux ranges in phase „A” in the central column and in phase „B”, the subsequent column. Table 4-3. shows that at zero residual flux values (this is the area of column 6, row 6 in Table 4-3) the highest value of the flux peak is optimal (110%).in other fields of the table the maximal flux gets higher, if the „distance” from this optimal field increases. Especially high values can be found, if the residual flux is high Column and row values at 1 or 10. The experiences show however that the swings by the internal capacitances and inductances can decrease the residual flux values, so these extreme fields cannot be measured. Some fields are not filled. This means that these flux combinations are not possible theoretically.

As a summary the fixed A-B-C switching sequence with timing stored in a table can minimize the flux values and so the inrush current peaks, but the optimal switching (110% flux overshot) can generally not be guaranteed. A flux overshot of about 160 % must be expected, but the experiences show that the current peaks are limited below the rated current peak range. The advantage of the method is that phase “A” can generally be selected as the reference phase, and from the power supply side voltages this one serves as the basis of time delay.

B A	1	2	3	4	5	6	7	8	9	10
1					115	150	**163**	**184**	**190**	**211**
2					115	136	**163**	**177**	**190**	**204**
3				115	115	129	**156**	**170**	**184**	**204**
4		**156**	136	115	110	129	**156**	**170**	**184**	**190**
5		**156**	150	129	115	115	129	**156**	**163**	**177**
6		**163**	**156**	129	115	110	136	150	**156**	**163**
7	**190**	**184**	**163**	**156**	129	110	122	143	134	**156**
8	**190**	**184**	**163**	**156**	136	115	122	136		
9	**197**	**184**	**177**	**163**	143	115	110			
10	**204**	**184**	**184**	**163**	150	110	110			

Table 4-3. Highest flux values using circuit breakers with common drive and 5-0-5 ms mechanical time delay

This mode of operation is favorable only if the residual flux values – because of the shape of the magnetizing curve – are relatively low.

Remark: concerning the peak values of the inrush current, no exact value can be predicted. To calculate the value the source impedance, the full magnetizing curve of the iron core, the exact construction of the iron core, the structure of the coils etc. must be known. It is obvious however that if the flux value is limited to values not too high above the saturation value, then the inrush current is limited below the rated current peak value too.

4.4.2.2 Switching with 0-6.66-3.33 ms delayed common drives

In the introduction of chapter 4.4.2 it was mentioned that for shunt inductances, having iron cores individually for each phases are usually switched with circuit breakers of mechanically delayed common drives. In this case the phase sequence is A-B-C with mechanical time delay of 0-6.6666-3.3333 ms. If the residual flux is zero, then this mechanical time delay can result optimal switching sequence. It was mentioned too that if the residual flux values are not zero, the inrush current peaks cannot be eliminated with this control sequence. In case of transformers the combined iron core introduces further complications. When switching any of the phases, the induced voltage in other ones starts to change the flux immediately. Now apply the method of investigation in this chapter, and try to predict the effect of this time-delayed switching in case of YoD transformers with three-limb iron core.

The headlines of Table 4-4 show the residual flux ranges in phase „A" in the central limb of the iron core and in phase „B", the subsequent limb. "1" means small range of the negative peak and "10" means the small range of the positive peak. At "5" and "6" the residual flux value is near zero.

The values of this table show the relative flux overshot. It can be seen that in the middle of the table the flux values are relatively high (about 130 %), but the distribution is "flat" which means that the flux overshot can be kept within reasonable limits using this mechanical time delay of 0-6.6666-3.3333 ms.

B A	1	2	3	4	5	6	7	8	9	10
1					115	115	129	**156**	**163**	**163**
2					115	115	122	143	**156**	**163**
3				115	122	115	115	129	150	**163**
4		122	110	115	129	122	115	129	143	150
5		122	110	115	129	129	115	115	129	136
6		129	122	110	129	129	122	115	129	136
7	150	136	129	115	115	129	115	115	129	136
8	**156**	150	122	115	115	115	115	115		
9	**156**	150	143	122	115	115	110			
10	**163**	**156**	150	129	115	110	115			

Table 4-4. Highest flux values using circuit breakers with common drive and 0-6.66-3.33 ms mechanical time delay

The expected inrush current peak values cannot be eliminated fully, but they can be expected to be below the rated transformer current peaks.

Remark: concerning the peak values of the inrush current, no exact value can be predicted. To calculate the value the source impedance, the full magnetizing curve of the iron core, the exact construction of the iron core, the structure of the coils etc. must be known. It is obvious however that if the flux value is limited to values not too high above the saturation value, then the inrush current is limited below the rated current peak value too.

4.4.2.3 Switching with 0-0-0 ms delayed common drives

If the circuit breaker has a common drive and the mechanical construction is set to move the three poles of the phases together, then the consequence is a somewhat less favorable behavior than that of 5-0-5 mechanical time delay.

It must be pointed out that as the figures of Table 4-5 show, not an optimal flux overshot can be achieved, but they can be minimized.

It is remarkable that the highest flux values can be seen in the rows 5 and 6 and column 5 and 6. These are the states of small residual flux values. The values above 130% are highlighted with bold *letter*s. So this mode of operation is favorable only if the residual flux values – because of the shape of the magnetizing curve – are relatively high.

In most cases the hysteresis loop of the iron core material can however result relatively high residual flux values in the limbs. The experiences show that this kind of mechanical fixing the circuit breaker poles result acceptable small inrush currents.

B A	1	2	3	4	5	6	7	8	9	10
1					126	110	110	110	118	118
2					118	110	118	110	110	126
3				110	118	126	126	110	110	126
4		126	110	110	126	**150**	**150**	126	126	110
5		118	110	**142**	**157**	**173**	**157**	**134**	110	110
6		110	126	**142**	**173**	***189***	**142**	110	110	126
7		110	126	**142**	**142**	**142**	126	110	126	150
8	102	110	126	126	**134**	118	110	126		
9	110	110	110	110	110	126	126			
10		134	134	134	110					

Table 4-5. Highest flux values using circuit breakers with common drive and 0-0-0 ms mechanical time delay

4.5 Energizing the transformers from the delta side

The analysis above supposes a transformer switched from the grounded Y side. It was pointed out that during the energizing procedure no zero sequence flux and voltage is generated, no zero sequence current flows, so the delta connected secondary winding has no influence on the phenomena.

If however the transformer is energized from the delta side then some other facts must be considered.

When connecting a single phase voltage to the delta connected winding then there is no closed loop, no current is expected. The inrush phenomena start only if two phases are energized. In this case a full line-to-line voltage is connected to the winding between the two energized phases; the other two coils get half voltage, which is opposite to the supposed positive direction. This corresponds also to the flux distribution of the closed iron core. Consequently energizing two phases on the delta side is equivalent with energizing one phase on the grounded Y side.

If on the delta side the third phase is energized too, then the three-phase energized state results. From flux point of view this is equivalent to the state of two (or three) energized phases from the grounded Y side. As an example the mechanically delayed 5-0-5 ms common drive circuit breaker for the grounded Y side corresponds to 0-5-0 ms mechanically delayed circuit breaker on the delta side. With this change the inrush phenomena is the same. The controller function considers this equivalency.

As the structure of the transformer iron core is symmetrical to the central limb, in this realization it is important to energize first the two phases, which connect full voltage to the coil on the central limb. In case of individual drives for the phases this is assured by the software. If the phases of the circuit breaker are mechanically delayed then this fix delay should consider this requirement.

The Fig. 4-7 below shows a Dy11 arrangement. The coil of the central limb of the iron core is between S and T, accordingly these are the first contacts to be closed at energizing. The mechanical time delay to be arranged is in this case e.g. using 5 ms time delay: 5-0-0.

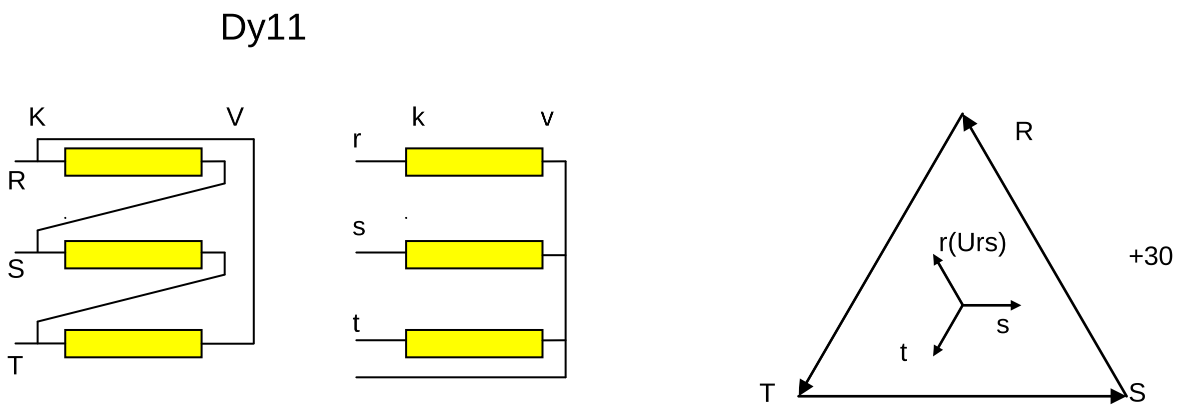

Fig. 4-7 Energizing a Dy11 transformer

If however the connection group is e.g. Dy7 then the coil of the central limb of the iron core is between R and S, accordingly these are the first contacts to be closed at energizing. The mechanical time delay to be arranged is in this case e,g using 5 ms time delay: 0-0-5. See Fig. 4-8 below.

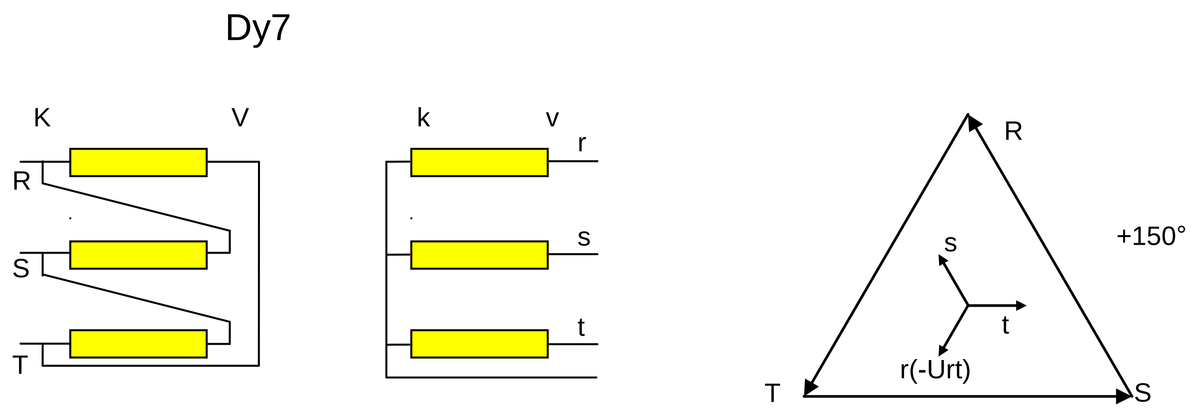

Fig. 4-8 Energizing a Dy11 transformer

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