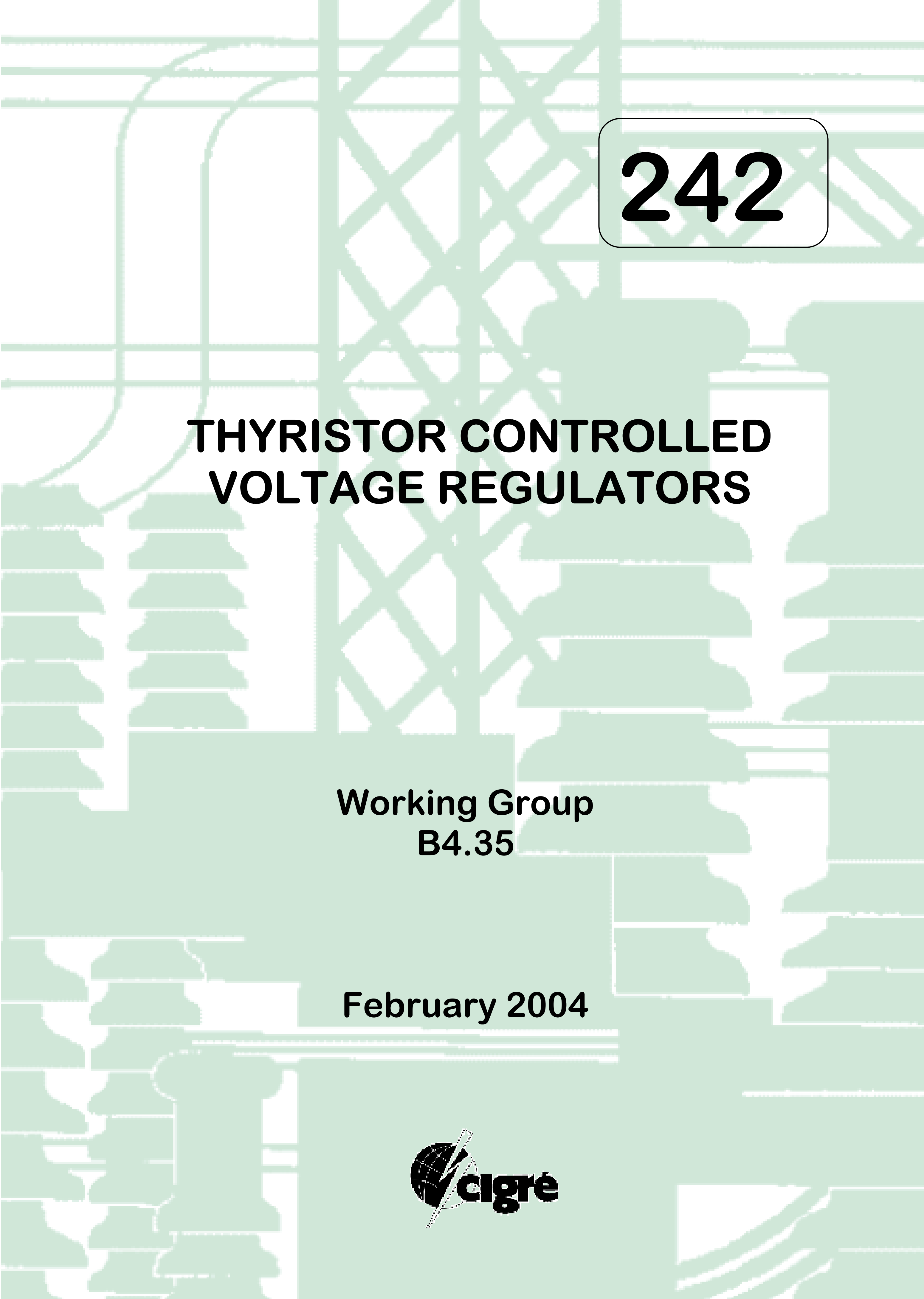

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THYRISTOR CONTROLLED VOLTAGE REGULATORS

Working Group
B4.35

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THYRISTOR CONTROLLED VOLTAGE REGULATORS

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THYRISTOR CONTROLLED VOLTAGE REGULATORS

SUMMARY

CIGRE Working Group for Thyristor Controlled Voltage Regulators was formed to explore non-conventional methods of voltage regulation of ac power transmission systems using thyristor-based power electronic devices. The report has two parts. In the first part three new non-conventional methods of voltage regulation by reactive power control are described. The Voltage Controlled Static VAR Compensator (VCSVS) regulates reactive power by varying the voltage applied to a reactive element, a capacitor or a reactor. Transformer secondary windings are arranged in different circuit configurations by thyristor switching to vary the voltage applied to the reactive element. The Shunt Capacitor Bank Series Shorting (CAPS) and the special delta-star switching, two simple practical methods of obtaining capacitor banks with dual ratings, are described. In the second part, the feasibility of Static On-Load Transformer Tap Changer (OLTC) is explored. Static OLTC with thyristor substitution of mechanical contacts of conventional OLTC would be prohibitively costly. Hybrid OLTCs in which static switches replace the diverter switches of the mechanical OLTCs are feasible, but their potential benefits are marginal. The most promising fully static OLTC is the one with switched windings.

I. Introduction

The CIGRE Working Group for Thyristor Controlled Voltage Regulators was formed to explore non-conventional methods of voltage regulation of ac power transmission systems using thyristor-based power electronic devices. This report presents the results of the efforts of the Working Group.

AC voltage being a phasor quantity, control of voltage could mean control of the magnitude and/or phase of the voltage. However, this report deals with only circuits for the control of the magnitude of the voltage.

In an ac system, typically, there are three methods of regulating the voltage magnitude:
1. Excitation control of the generators
2. Transformer tap changer control, and
3. Reactive power control.

The first widespread use of thyristor-based power electronic devices for voltage regulation was for excitation control of generators. It is now widely recognized as an effective economic means of voltage regulation in power systems. [1]. The subject is not discussed further in this report.

Tap changer control of power transformers is also a widely used method of voltage regulation. Most common is automatic tap changing on bulk power delivery transformers and distribution voltage regulators. Transmission network autotransformers often incorporate on-load tap changing (OLTC), often manually controlled using SCADA. Some companies use

OLTC generator step-up transformers to allow rated reactive power output over a range of transmission voltages.

Almost all tap changers use mechanical switches. Although mechanical switches are rated for hundreds of thousands of operations, failure of a tap changer on a large network autotransformer or generator step-up transformer is a serious concern. Utilities often limit tap changer operation on network transformers to several taps per day. In fact a stated benefit of SVCs and STATCOMs is the reduction of tap changer operation. Thus, electronic tap changing with unrestricted switching has the potential to enhance the reliability, particularly with respect to oil-based OLTCs, and would improve voltage control.

Fast tap changer operation can support voltage stability and prevent voltage collapse of the transmission systems. With motor load, tap changing can be beneficial to voltage stability. Following a disturbance, fast tap changing to regulate voltage near motors can prevent motor stalling and support power factor correction capacitor banks. Tap changing in the transmission network is usually beneficial to voltage stability, because downstream (load side) reactive power losses are reduced, and downstream line charging and shunt capacitor bank output is supported. Automatic tap changing on network transformers should be faster than tap changing on bulk power delivery transformers serving voltage sensitive load.

The above considerations indicate that benefits from static tap changers could be more than savings from eliminating the wear and tear of mechanical tap changers. Selective operation of fast-acting static tap changers, backed with high speed data acquisition and communications, has potential for significant system benefits.

Two types of on load tap changers using thyristor based power electronic equipment, a fully static one and a hybrid system which uses thyristor-type diverter switch and mechanical tap selector, are discussed in this report. An example of a GTO-based hybrid OLTC is also described in this report.

Static means of system voltage control by reactive power regulation is the object of different types of static VAR compensators. At present there are two broad categories of static VAR systems:

1. Static VAR compensators based on reactive power consumption or generation by reactors and or capacitors;
2. STATCOMs.

STATCOMs are based on the application of a sinusoidal voltage source different from the power system voltage, developed by power electronic circuits, to draw from, or inject into, power system the reactive power by controlling the magnitude of this separately created voltage source. CIGRE Report "Static Synchronous Compensators(STATCOM)" explains such systems in more detail [2]. This type of SVC is based on GTOs.

At present there are three types in the first category of SVCs [3]:

1. Thyristor Switched Reactors (TSR);
2. Thyristor Switched Capacitors (TSC); and
3. Thyristor Controlled Reactors (TCR).

In the case of TSR and TSC, back-to-back connected thyristors are used to switch on or off reactors or capacitors to control the reactive power supply. Such on/off control gives discrete step changes in reactive power supply. In the case of TCR, back-to-back connected thyristor valves are used not only to turn on or off the SVC, but also to vary the reactive power supply by adjusting the firing angles of the thyristor valves. Varying the firing angle varies the conduction period of the reactor, changing the effective impedance of the reactor. Unlike TSR and TSC, TCR allows continuous control of the reactive power. However, the discontinuous current through the reactor produces harmonics, which requires harmonic filters. The filters add cost, including cost of additional losses.

There is also the Thyristor Controlled Transformer (TCT). This can be considered a special form of TCR. In this type of SVC, the secondary winding of an SVC transformer is shorted through back-to-back connected thyristors. The leakage reactance of the shorted transformer winding takes the place of the reactor in a regular TCR. A few SVCs of this type were installed in the 1970's in the Hydro-Quebec system in Canada.[4]**.** Otherwise they did not find favor with the industry. However, there have been some recent attempts to revive interest in this type of SVC. [5].

This report presents three new static methods of reactive power regulation. One is a new type of static VAR compensator called Voltage Controlled Static VAR Compensator. The second one is a static version of CAPacitor bank Series Shorting (CAPS) scheme introduced by Bonneville Power Administration (BPA) [6]. The third one is a novel static switching scheme to configure a shunt capacitor bank in delta or star connection. None of these schemes has been implemented in a commercial system yet.

II. Static Reactive Power Regulation

II.1. Voltage Controlled Static VAR Compensator (VCSVC)

II.1.1 Basic Circuit

In the proposed method, voltage is applied to the capacitor or reactor through a transformer with multiple secondary windings with provision for static switches to connect the secondary windings in different ways to vary the applied voltage in small steps. The transformer is provided with a fixed winding W_f and a number of control windings. Each of the control windings is connected to four bi-directional static switches,made up of back-to-back connected thyristor valves, arranged in a bridge circuit. Figure II.1 shows such an arrangement with two control windings for a Voltage Controlled Thyristor Switched

Capacitor (VCTSC). Similarly, arrangement for a Voltage Controlled Thyristor Switched Reactor (VCTSR) with three control windings is shown Figure II.2.

By turning on the right pair of these thyristor valve switches while blocking the other pair, it is possible to have the corresponding control winding connected in three different ways: (1) in series with the fixed winding W_f with the voltages of the fixed winding and the corresponding control winding(s) in phase; (2) in series with the fixed winding with the voltages of the fixed winding and the corresponding control winding(s) in phase opposition; or, (3) the control winding(s) bypassed.

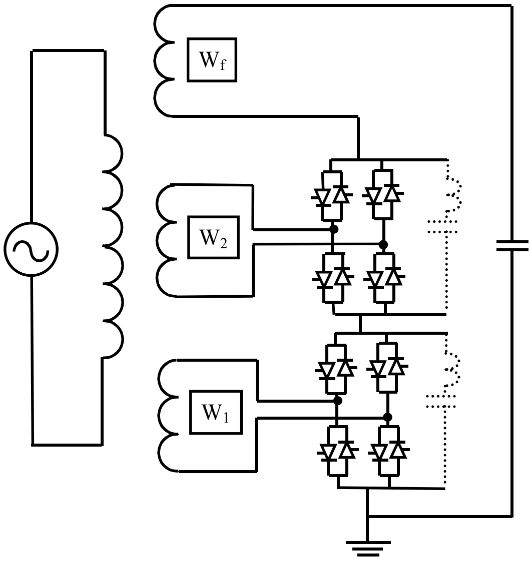

Figure II.1: Voltage Controlled Thyristor Switched Capacitor (VCTSC)

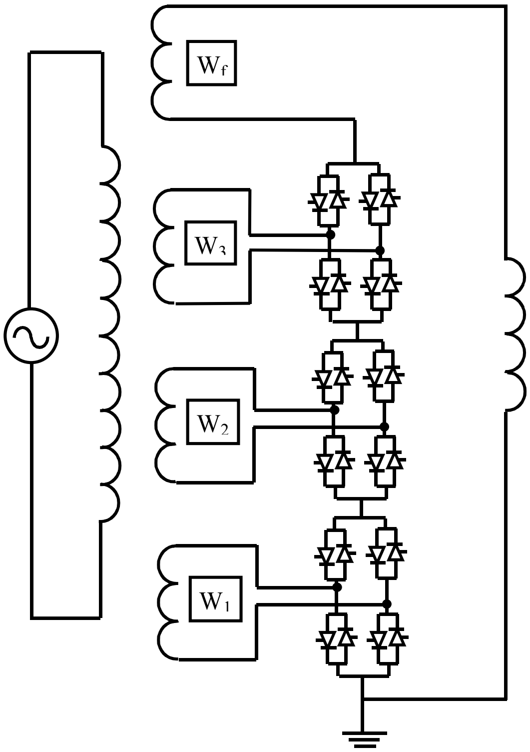

Figure II.2: Voltage Controlled Thyristor Switched Reactor (VCTSR)

Under certain conditions, the attempt to change the current conduction path in the bridge by thyristor valve switching could fail due to commutation failure. This problem is explained in more detail in the section on Transformer Tap Changers (Section III.1). The problem can be eliminated by taking two steps: (1) the firing of the incoming pair of valves is delayed by the turn-off time of the valves after current zero in the pair of outgoing valves; and, (2) connecting a bypass capacitor or a series L-C circuit between the nodes of the bridge not connected to the transformer winding. The connection of the bypass L-C circuit is shown in Figure II.1. For simplicity of presentation, the bypass circuit is not shown in the other figures.

The number of control windings and their voltage ratings determine the number of steps and the step sizes. To obtain uniform step sizes with minimum number of control windings, the voltages of "n" control windings are chosen to be V_1, $3\ V_1$,…. $3^{(n-1)}\ V_1$, where V_1 is the smallest step size. In Figure II.1, with two control windings, it is possible to get nine combinations of the applied voltages: V_f, $V_f \pm V_1$, $V_f \pm 2\ V_1$, $V_f \pm 3\ V_1$ and $V_f \pm 4\ V_1$, where V_f is the voltage of the fixed winding. If $V_f = 4\ V_1$, the voltage applied to the capacitor can be varied from zero to $8\ V_1$ in eight equal steps. Since zero voltage can be obtained with all the valves blocked, making $V_f = 5\ V_1$ will provide nine voltage steps from zero to $9\ V_1$.

Similarly, with 3 control windings, as shown in Figure II.2, it is possible to get 27 step changes in the voltage applied to the reactive element. In general, if there are n control windings, one could get 3^n steps.

The voltage changes are in discrete steps and not continuous. However, from a practical point of view, the step sizes can be made as small as necessary by increasing the number of control windings – in principle as small as to be indistinguishable for a given measurement accuracy. The reactive power control is usually for the purpose of controlling the system voltage, which normally does not have to be controlled to a precise value, but have to be kept only within a certain band. It is therefore adequate if the step change in voltage applied to the reactance is small enough that the resultant change in reactive power supply causes system voltage change small compared to the specified voltage band.

It is possible to make the reactive power control of the device truly continuous by having an extra secondary winding which supplies a TCR. The size of this need not be large, only as large as the largest step change in reactive power for step changes in the voltage applied to the reactive element. Then, the coarse control of the reactive power supply will be by the step changes in the voltage applied to reactance element and, between steps, additional fine control would be obtained by the control of the TCR. The size of the TCR could be made small enough to make harmonics resulting from TCR operation too small to require any harmonic filters. Such a refinement with a small TCR is not likely to be needed in most cases. Therefore, further consideration of this type of SVC in this report is limited to those without the TCR part.

Instead of the fixed winding all the windings could be made control windings. However, this would increase the total ratings of the static valve switches without a proportionate increase in number of steps.

It is not necessary, nor is it always desirable, to make all voltage steps equal. Reactive power is proportional to the square of the applied voltage. When the voltage applied to a reactance is changed from V to V + V_1, the change in reactive power is $V_1^2 + 2VxV_1$. The higher the initial value of the voltage, the greater will be the step change in reactive power. So a larger step change in applied voltage might be acceptable for the first step. One way to make only the first step large and the remaining steps equal is to make the voltage of the fixed winding relatively large. For example, in the case depicted in Figure II.1 with two control windings, if $V_f = 9\ V_1$, the minimum value of the applied voltage will be 5 V_1, and each step after that will be in increments of V_1. In terms of reactive power generated by the SVC, this first step corresponds to only $(5/13)^2$, or less than 15%, of the full output of the SVC.

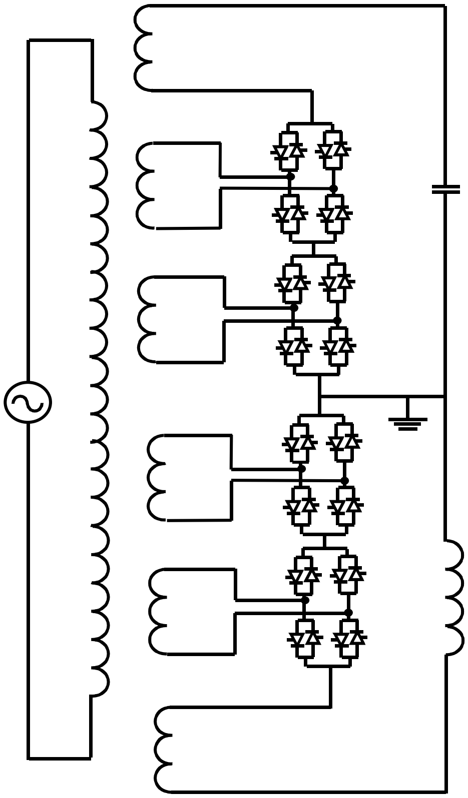

Figure II.3: Voltage Controlled SVC combining VCTSC & VCTSR

There are number of ways the arrangements for capacitive and inductive reactive power supply can be combined to get a Voltage Controlled Static VAR Compensator (VC SVC) with specified range extending from inductive to capacitive MVAR. One method would be to have separate transformer secondary windings with their own valve groups as shown in Figure II.3. In this case it is not necessary to have the TSC and TSR parts to have the same secondary windings arrangement in terms of the number of windings or their voltage ratings. In another arrangement, shown in Figure II.4, both TSC and TSR parts can share the same transformer secondary windings but separate valve groups. Since the effect on system voltage of increasing capacitive MVAR is the same as reducing inductive MVAR, it is not necessary to have step control on both TSC and TSR parts. An economical arrangement, therefore, would be to have only the TSC part subject to step control and TSR part connected either to the fixed winding of the VCTSC or to a separate secondary winding on the same transformer. An arrangement of VCSVC with the TSR part on the fixed winding is shown in Figure II.5.

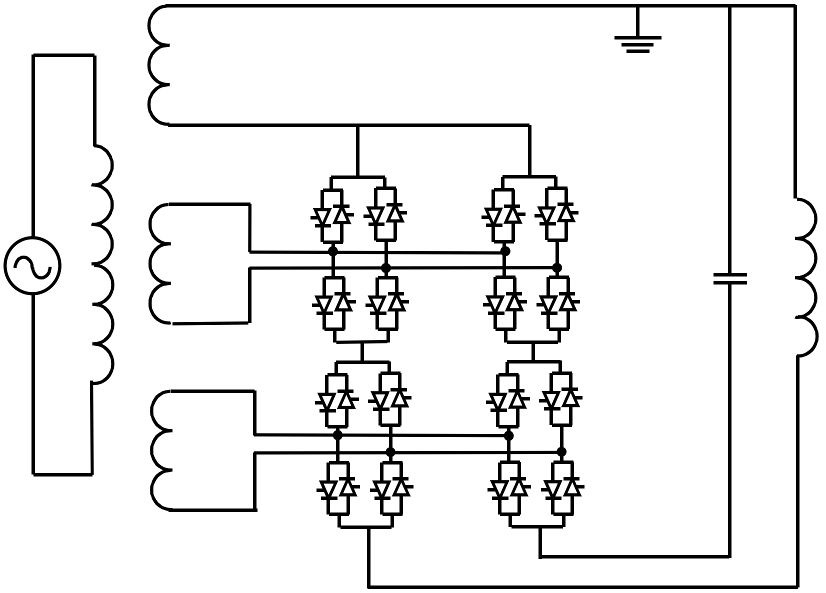

Figure II.4: Voltage Controlled SVC with common transformer secondary windings for VCTSC and VCTSR

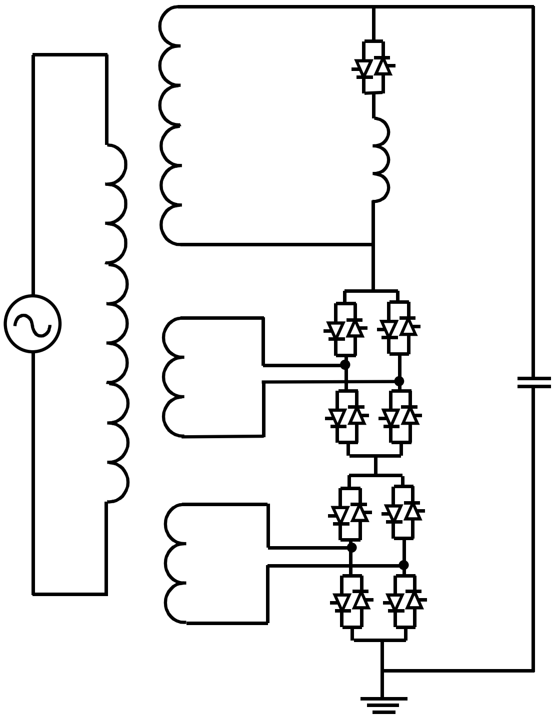

Figure II.5: Optimum Circuit arrangement for VCSVC

II.1.2. Equipment Ratings

Most of the time, conventional SVCs operate with their own step down transformers either because the system ac bus voltages are high or to obtain optimum thyristor valve ratings. The Voltage Controlled SVCs and conventional SVCs of similar rating will have transformers of the same rating. The only difference is the need to have the secondary side split into three or four windings in the case of VCSVCs. Short-circuit duty of these windings would be different and should be taken into consideration. Available information indicates that the increase in the cost of the transformer would not be very significant.

To get a general understanding of the sizing of the thyristor valves, we make the assumption that the valve costs are proportional to the number of thyristor levels and that the number of thyristor levels is proportional to the rms value of the ac voltage applied to it, and ignore thyristor redundancy margins. We further assume that the transformer voltage ratings are selected to provide optimum current rating for the thyristor valves. Consider Figure II.6.

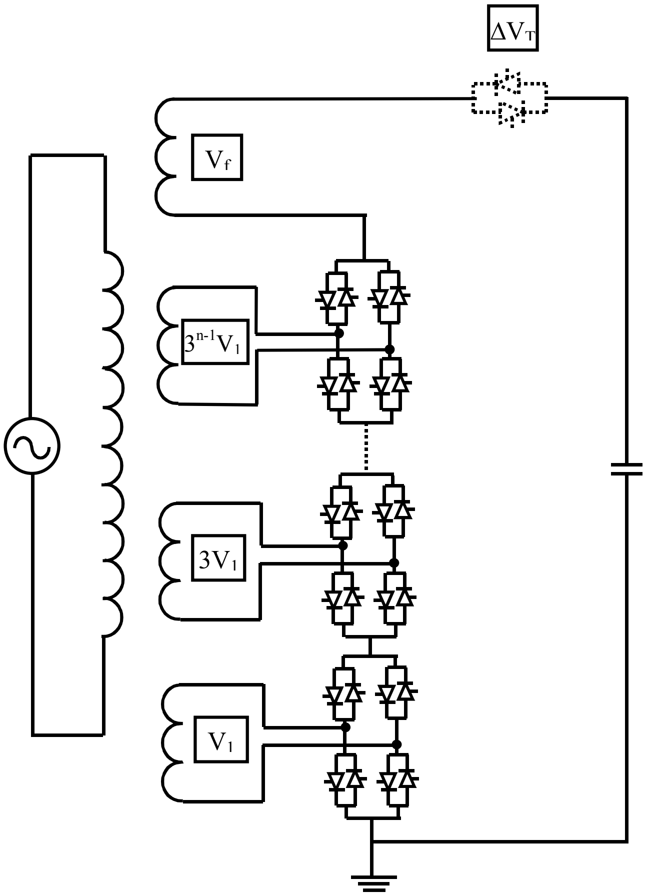

Figure II.6: VCSVC with supplemental valve

The smallest voltage step size is V_1. If the voltage of the fixed winding is V_f, the maximum output voltage applied to the reactive element, V, is

$$V = V_f + (V_1 + 3\ V_1 + \ldots + 3^{(n-1)}\ V_1) = V_f + V_c \text{ where}$$

$$V_c = (V_1 + 3\ V_1 + \ldots + 3^{(n-1)}\ V_1)$$

Where n is the number of control windings.

Recognizing the 4 arms of the bridge circuit connected to each control winding, the total thyristor voltage rating, V_T, is

$$V_t = 4Vc$$

If $V_f = KV_c$

$$V_T = \frac{4}{(1+K)} V$$

The above equation shows:

1. The thyristor voltage rating is independent of the number of control windings, i.e., one could obtain necessary fineness in voltage control without significant penalty in total thyristor valve ratings.

2. The larger the voltage rating of the fixed winding, the lower the relative voltage rating of the thyristors. If K=1, i.e., the voltage rating of the fixed winding is equal to the sum of the voltage ratings of the control windings, $V_T = 2V$. In this case each step, including the minimum voltage will be equal.

If K is greater than 1, the relative voltage rating of the thyristor valves would be reduced. For example, if K=2,

$$V_T = \frac{4}{3} V$$

In this case the minimum voltage, V_{min}, is increased.

$$V_{\min} = \frac{1}{3} V$$

As pointed out earlier, since reactive power is proportional to the square of the voltage, a minimum non-zero voltage of

$$\frac{1}{3} V_{\max} \left(or \ \frac{1}{9} Q_{\max} \right)$$

is not likely to be a problem. In line with above reasoning that establishes the voltage withstand capability of the valves entirely on the voltages applied by the control windings, it is possible to further reduce the voltage rating of the thyristor valves by increasing the value of K. However, one has to also consider the required voltage withstand capability of the valves when SVC is blocked. In this case, the voltage of the fixed winding is applied to all the thyristors of the control windings connected in series. Each control winding valve bridge has two series connected valves providing this blocking capability. The total thyristor voltage rating would be sufficient for $K \leq 2$. This would indicate that the optimum arrangement for minimum thyristor valve rating would be K=2. However this needs to be qualified by a few other considerations:

(1). The blocking capability of thyristor valves in the circuit could be bolstered by adding thyristor levels in series with the fixed winding without increasing the number of thyristors in the bridge circuits connected to the control windings. This is shown in Figure II.6.

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The voltage rating of the extra series valve ΔV_T, will be

$$\Delta V_T = (K-2)V_c$$

and the total valve rating, V_T, will be

$$V_T = \left[1 + \frac{1}{(1+K)}\right] V$$

For example, for $K = 3, V_T = 1¼$V

(2) In the blocked condition, the thyristors connected to a control winding has to withstand not only the voltage of the fixed winding, but also that of the control winding.

(3) In the case of VC TSC, residual charge in the capacitor in blocked condition could require increased withstand voltage capability for the valves. An economical way of providing it, if the voltage rating of the valves in the bridge circuit is inadequate, would be to provide extra valve in series with the control winding as shown in Figure II.6. However, there are control steps that can be taken to reduce or eliminate this residual charge in the capacitor by bringing the capacitor voltage to zero or to a small value before blocking the valves.

(4) When the valves for the control windings are provided with redundant thyristor levels, it may be feasible to increase the value of K above 2 without providing the additional valves in series with the fixed winding. Redundancy is normally specified in terms of a certain percentage of the total number of thyristors in series. In valves with only a few thyristors in series, as is likely to be the case for thyristor valves in the control windings, the actual percentage redundancy will be higher due to the need to provide a whole number, not a fraction, of redundant thyristor levels. This could mean that the series connection of thyristor valves of different control windings could provide voltage blocking capability more than that which is needed for K = 2 even after allowing for required redundancy for the blocked condition.

II.1.3. Comparison with Conventional SVCs

VCTSC Versus TSC

Transformer rating: MVA ratings same for both. VCTSC requires secondary to be split into three or four windings. Typically, these are low voltage windings, and as such do not add significant design complexity. A small increase in the cost of the transformer is to be expected.

Thyristor Valves: Conventional TSC requires thyristor levels with voltage rating at least twice the maximum transformer applied voltage. The thyristor levels for the VCTSC valves with voltage ratings corresponding to the maximum transformer voltage. However, VCTSC valves are arranged in bridge circuit which requires two parallel strings of thyristors, each with full voltage withstand capability. Therefore, the total number of thyristors in both cases is likely to be of the same order.

Controllability: VCTSC is much better as it is able to provide the fine control without the aid of a TCR. Paralleling of conventional TSCs to obtain a level controllability comparable to that of VCTSC would make conventional TSC much more expensive.

VCTSR Versus TCR

Transformer rating: Issues of complexity and additional cost of splitting transformer secondary windings are the same as in the case of comparison between TSC and VCTSC.

Reactor: Harmonic losses in the reactor would make the reactor of TCR slightly more expensive.

Thyristor Valves TCR is likely to require fewer thyristor levels. Firing angle control increases complexity and costs of the control system and increases valve losses for TCR.

Controllability: Theoretically TCR is better, but from a practical point of view there is no significant difference.

Harmonic Filters: Absence of filters is a major advantage of VCTSR.

VCSVC versus SVC

An arrangement of VCSVC as shown in Figure II.5 combines all the benefits of VCTSC over TSC and those of VCTSR over TSR without the drawback of increased thyristor levels for VCTSR compared to TCR.

Economic Comparison

The economic viability of the new concept was investigated by comparing the cost and losses of a VCSVC and a conventional SVC. In order to get a realistic assessment, the example chosen was a commercial project for a conventional SVC for which one manufacturer had successfully bid and supplied the equipment. The functional specifications and the loss evaluation methods were those established by the utility. The SVC ratings were 150MVAR inductive and 250MVAR capacitive. Based on the more detailed specifications for the project, the conventional SVC solution selected was as shown in the schematic diagram of Figure II.7(a).

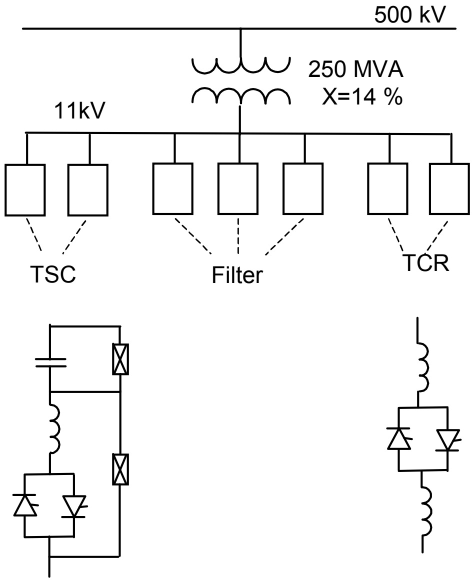


Figure II.7(a). Circuit configuration of conventional SVC with TSC and TCR

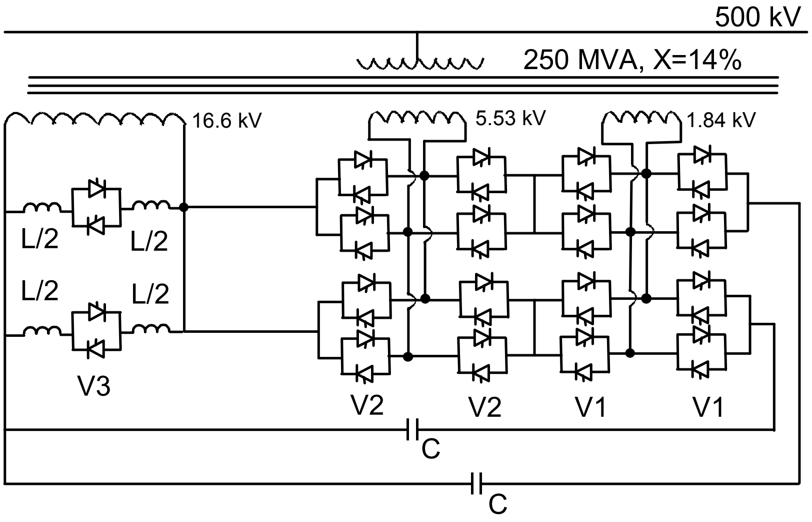


Figure II.7(b). Circuit configuration of the VCSVC with VCTSC and VCTSR

A scheme for an alternate solution based on the proposed Voltage Controlled SVC, meeting essentially the same functional requirements as for the conventional SVC, was developed by the same manufacturer. This is shown in Figure II.7(b). For this VCSVC a preliminary design, sometimes known as "Basic Design" in the industry, was carried out. The procedures followed were similar to those used for the conventional SVC at the bidding stage to estimate the cost of major equipment and of guaranteed losses. Loss determination considered no load and load losses in all the major equipment – transformers, thyristor valves, reactors and capacitors.

Comparing the cost of equipment, in the case of VCSVC, substantial savings from the elimination of harmonic filters more than offset the small increases in the costs of the thyristor valves and the transformer. Estimated total equipment cost for the VCSVC was found to be 5% less than that for the conventional SVC.

The savings in losses were even more pronounced. Losses for the two types of SVCs as a function of the reactive power output is shown in Figure II.8. Over the entire range, the average losses for the VCSVC and SVC are 650kW and 1150kW respectively. The losses were evaluated at $4800 per kW. Based on the evaluation criteria used by the utility, the cost of losses for VCSVC was 40 % less than that for the conventional SVC.

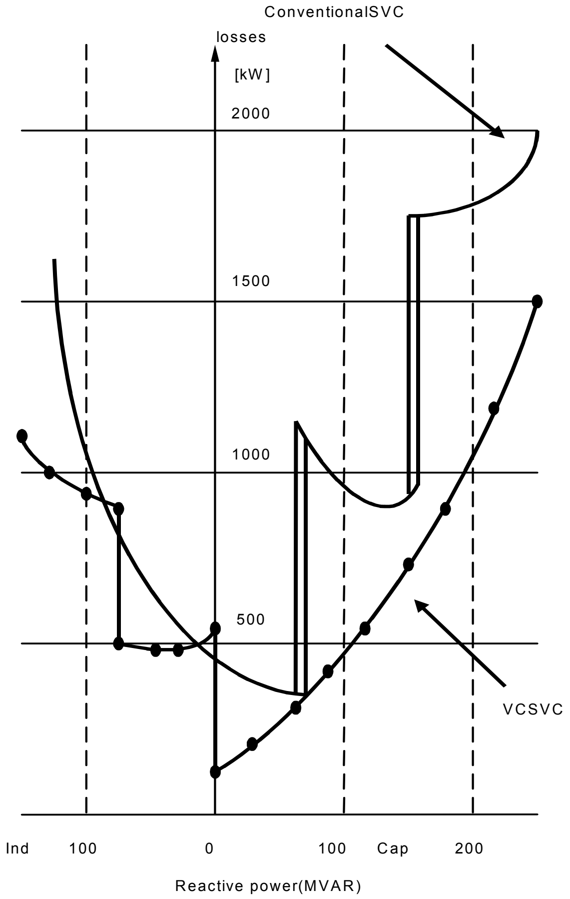


Figure II.8: Comparison of losses between conventional SVC and VCSVC

Combining the cost of equipment and losses, the total cost of the VCSVC solution was 15% less than that for the conventional SVC.

II.1.4 Simulation Results

A Voltage Controlled Thyristor Switched Capacitor rated 250 MVAR with two control windings as shown in Figure II.1 was simulated on PSCAD/EMTDC [7]. The ratio of V_f / V_c was 9/4. The VCTSC is connected to an ac system with a short circuit capacity of 4 GVA. Figure II.9 (a) shows the response of the circuit for a step change in the bus reference voltage from 1.00 pu to 1.05 pu. and back to 1.00 pu. . Figure II.9 (b) shows the response of the circuit when the reference voltage is ramped from 1.00 pu to 1.07 pu and back to 1.00 pu.

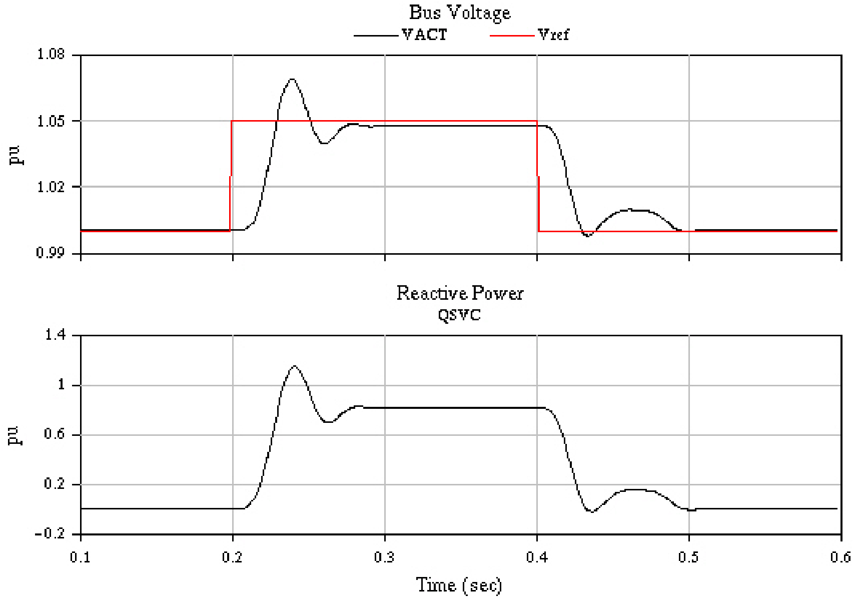


Figure II.9a: VCTSC response to a step change in reference voltage

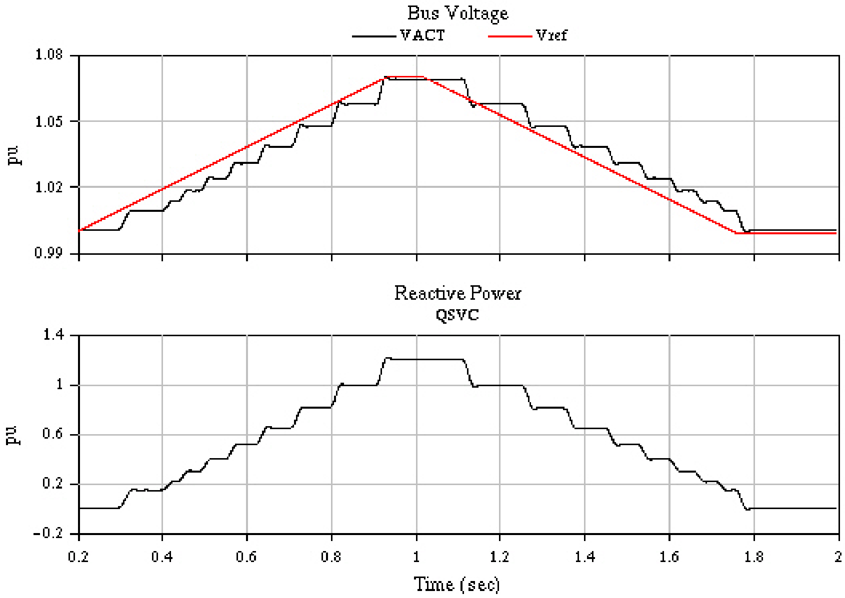


Figure II.9.b: VCTSC response when Vref is ramped up and down

A Voltage Controlled Thyristor Switched Reactor rated 250 MVAR with three control windings as shown in Figure II.2 was also simulated on EMTDC. In this case the ratio of V_f / V_c was 33/13. The Short Circuit Capacity of the connected ac system is 4 GVA. Figure II.10 (a) shows the response of the circuit for a step change in the reference voltage from 1.00 pu to 0.95 pu and back to 1.00 pu. Similarly, the response of the circuit when the reference voltage was ramped from 1.00 pu to 0.936 pu and back to 1.00 pu is shown in Figure II.10 (b).

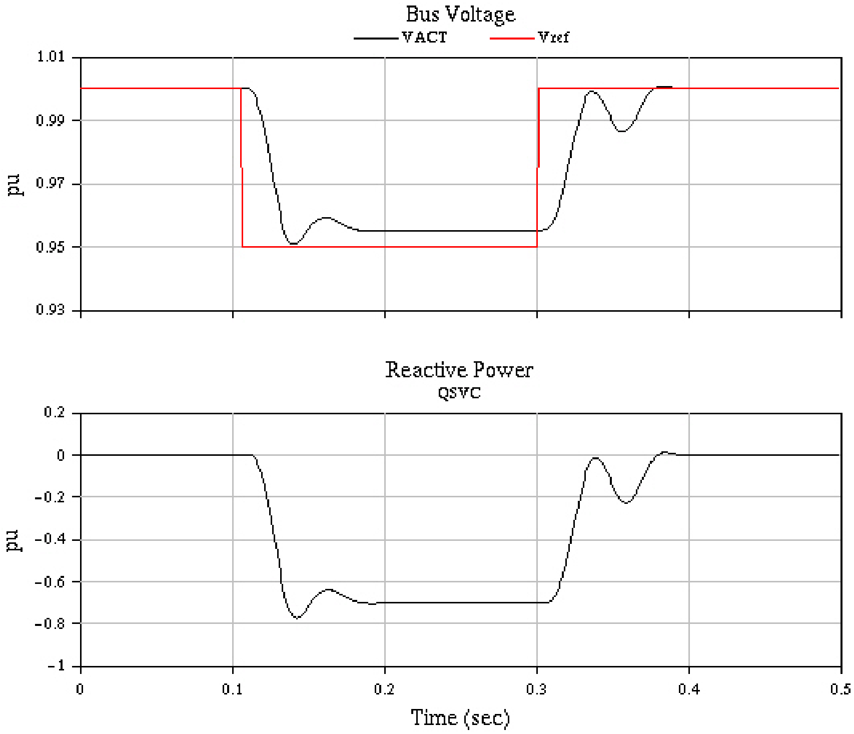


Figure II.10a: VCTSR response to a step change in Vref

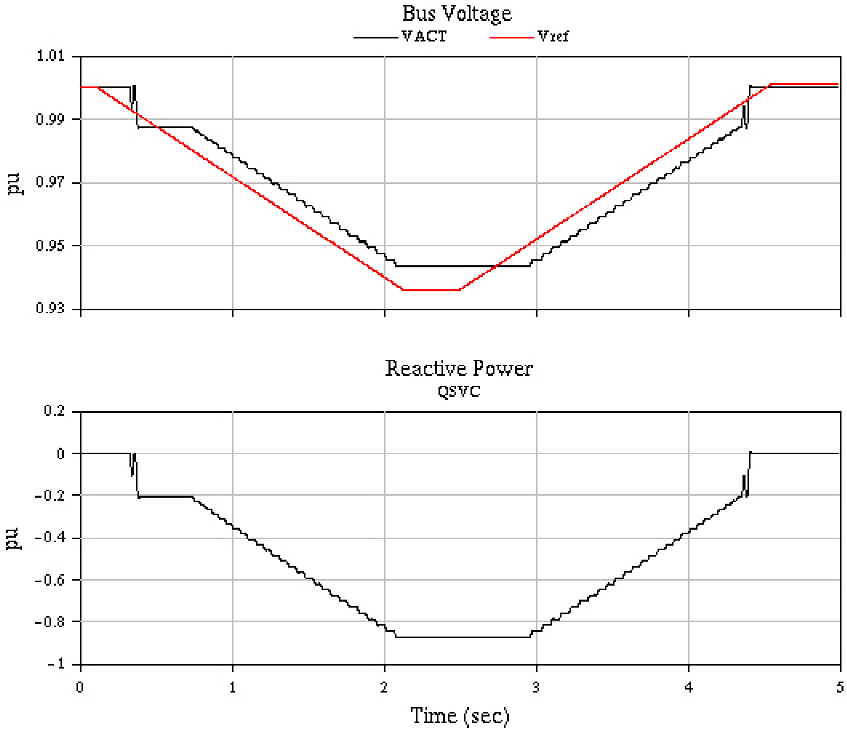


Figure II.10b: VCTSR response when Vref is ramped up and down

A Voltage Controlled Static VAR System with two control windings, rated +250MVAR to –125MVAR, with the TCR part connected to the fixed winding as in Figure II.5, was also simulated on EMTDC. Its response to step changes in bus reference voltage from 0.98 pu to 1.05 pu and back is shown in Figure II.11 (a). The response of the circuit when the reference voltage was ramped from 0.96 pu to 1.07 pu is shown in Figure II.11 (b).

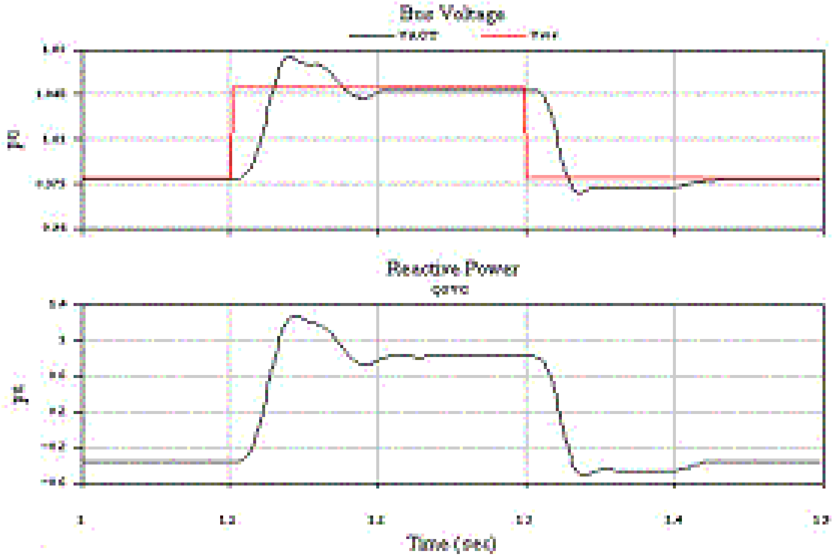


Figure II.11a: VC SVC response to a step change in Vref

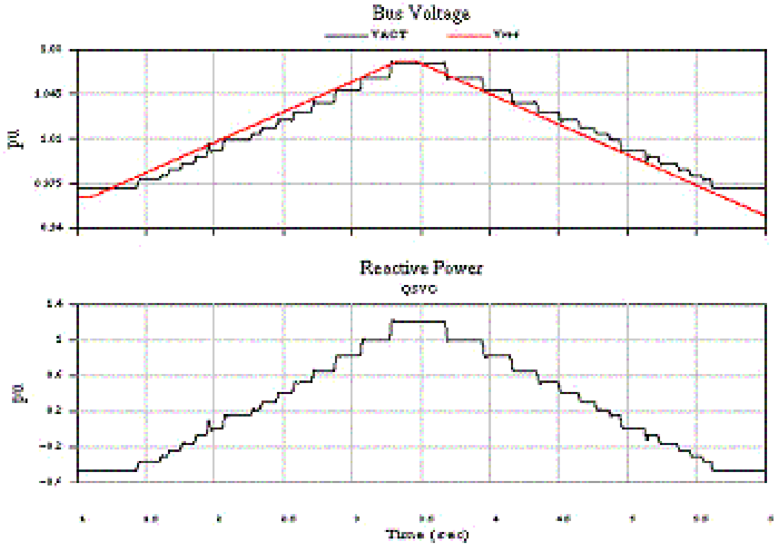


Figure II.11.b: VC SVC response when Vref is ramped up and down

II.2 Shunt Capacitor Bank Series Shorting (CAPS)

II.2.1 Background

The reactive current and reactive power outputs of a shunt capacitor bank are:

$I_c = V / X_c$, $Q_c = V^2 / X_c$

If a disturbance causes a voltage drop, a capacitor bank reactive power and current will decrease. This will tend tocause further voltage drop, which will cause further decrease in reactive power and current. A solution to this voltage versus output "unstable" characteristic may be found in the denominator — by decreasing the capacitive reactance during low voltage.

The Bonneville Power Administration (BPA) developed a new shunt capacitor bank scheme termed CAPS (CAPacitor bank series Shorting). CAPS uses a shorting switch and can exploit the time-overvoltage capability of capacitors. This method was successfully applied to an existing 241.5-kV, 168 MVAr shunt bank [6]. Mechanical switching was used.

Following this retrofit application, the Electric Power Research Institute (EPRI), BPA, and General Electric collaborated in a "clean sheet of paper" design study to optimize the application of CAPS for new HV and EHV shunt capacitor banks [8,9]. The design study encompassed all aspects of capacitor bank design: capacitors, capacitor arrangement, switchgear, fusing (external, internal, and fuseless), protection, risk, and economics. The design study developed and examined pros and cons of various design options involving standard, readily available components. Designs for temporary and continuous operation in the shorted condition were developed. The EPRI study emphasized mechanical switching, but also included preliminary analysis of thyristor control. Voltage collapse is often a problem only during combinations of high loading and major outages. Large investments are not cost-effective for such low probability events. CAPS can use the short-time reactive power capacity of a shunt capacitor bank such as the 30- minute time-overvoltage capability of the capacitors. CAPS compensates for the voltage-squared reactive power characteristic during periods of low voltages by shorting several series groups of capacitor units. The resulting additional reactive power output provides temporary voltage support during which corrective actions such as generation rescheduling, line restoration, or operator-directed load tripping can be completed.

Fused capacitor banks have groups of paralleled capacitor units connected in series, while fuseless capacitor banks have paralleled series strings of capacitor units [10]. For fuseless banks, bussing of the strings is required at the shorting point to form two series sections. The increase in capacitor bank output with shorting of series section is proportional to $n/(n - n_S)$, where n is the number of series units and n_s is the number of shorted groups. Figure II.12 shows a simplified schematic of the CAPS concept.

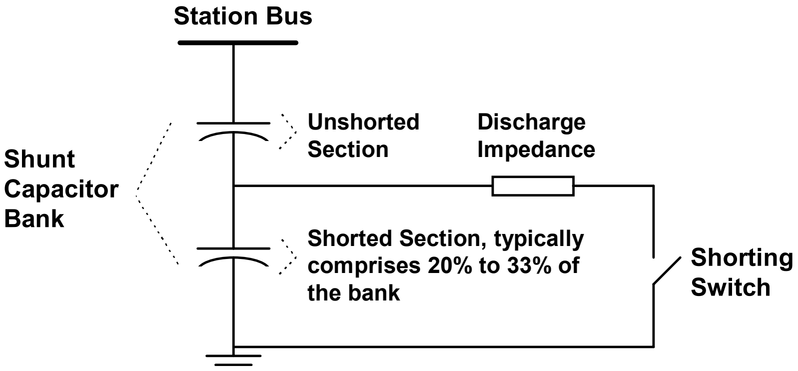


Fig. II.12: Simplified CAPS Schematic

In a voltage stability application with mechanical switches, CAPS operation would be initiated only during low network voltage conditions. Figure II.13 shows an example reactive power characteristic for a 230-kV shunt capacitor bank with and without the shorting switch closed. The vertical lines ignore the change of system voltage because of switching. A controller with hysteresis closes the switch at lower voltages and opens the switch at higher voltages.

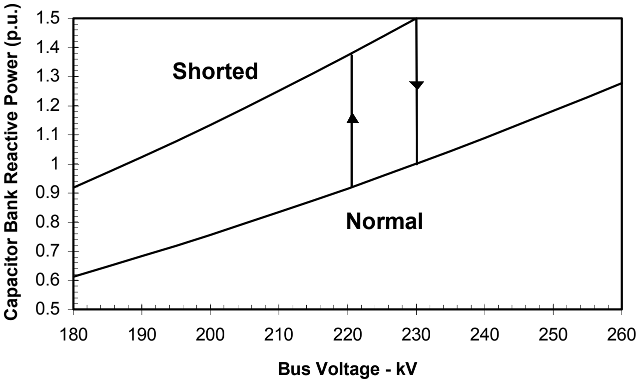


Figure II.13: Example reactive power characteristic with and without CAPS in service

The concept is similar to series capacitor banks where the time-overvoltage capability of the capacitors is exploited for parallel line outages. For both series and shunt banks, the overall bank must be designed for the overvoltage.

A CAPS bank can also be designed for continuous operation in the shorted condition, resulting in a two-step capacitor bank.I.2.2 CAPS with Thyristor Switching or Phase Control

CAPS operation with mechanical switching may be used only during infrequent low voltage emergencies. With continuous rating in the shorted condition, mechanical switching would still be relatively infrequent, perhaps several times per day.

It’s difficult to justify electronic switches for infrequent switching. It may be possible, however, to compete with a conventional SVC. CAPS with thyristor control would be a *transformerless* SVC. CAPS could be competitive if economical outdoor valves with simple cooling were developed. For simplicity in the analysis below, we assume that reactive power output changes do not substantially change network voltage. This would not be true for weak systems. Droop control is also not considered.

Thyristor phase control: CAPS with thyristor phase control was evaluated in the EPRI/GE study [9]. A thyristor controlled reactor replaces the mechanical switch. The TCR in parallel with a series section is similar to a thyristor controlled series capacitor (TCSC). Similar to a TCSC, there is a resonance region that must be avoided. Depending on firing angle, the capacitor with parallel TCR can be either capacitive (termed Mode 1) or inductive (Mode 2). Similar to a TCSC, time overvoltage capability in either mode can exist (e.g., 10 second rating or 30-minute rating). Also similar to a TCSC, harmonics would be largely confined to the capacitor bank.

In the EPRI study example, a capacitor bank with nominal rating of 525-kV and 350 MVAr was chosen, with 15% of the bank controlled. The 30-minute control range at nominal voltage is about 300–350 MVAr in Mode 1 and about 417–525 MVAr in Mode 2. The range 350–417 MVAr is forbidden; 0 MVAr output is of course also possible. The valve rating for 30 minute rating is 80 kV rms, 1300 A rms.

Comparison with a conventional SVC is difficult because of the forbidden region. The comparison could, for example, be with a 350 MVAr mechanically switched bank (MSC) and a SVC with 50 MVAr TCR and 175 MVAr TSC. The control ranges would then be -50–0 MVAr, 125–175 MVAr, 300–350 MVAr and 475–525 MVAr. The 30-minute coupling transformer rating would be 175 MVAr, and a small harmonic filter may be required. Admittedly, we are not comparing functionally equivalent systems.

Comparisons would depend on reactive power ratings and voltage level. CAPS might be more competitive at higher voltage because of the increased cost of conventional SVC coupling transformers. However, the SVC could be connected at a lower voltage than the MSC.

Thyristor switching: References 10 and 11 describe a 550-kV, 460/691 MVAr bank with 24 units in a series string, eight of which are shorted for the 150%(460 to 691 MVAr) boost. There are 18 series strings in parallel, and bussing is required at the shorting point.

The voltage of each series unit is 13.23 kV rms. With change to nine shorted units for 160% boost to 736 MVAr, a binary switching arrangement could be used with one set of thyristor valves shorting three series units and a second set shorting six series units. The valve voltage ratings would be 40 and 80 kV. The bank output values would then be 0/460/526/613/736 MVAr.

The cost of this bank could be compared, for example, against a 460 MVAr mechanically switched bank, and a SVC consisting of 92 and 184 MVAr TSCs (or three 92 MVAr TSCs). The output values would be 0/92/184/276/460/552/644/736 MVAr. For continuous operation, the coupling transformer rating would be 550-kV, 276 MVAr.

The conventional SVC/MSC obviously has more controllability. The cost of the high voltage valves for the CAPS scheme would have to be substantially less than the TSCs and coupling transformer. In many substation applications, the SVC could be connected at a lower voltage, reducing the coupling transformer cost.

II.2.3 Summary

Using CAPS, a transformerless SVC could be realized. Comparison with conventional SVCs (and static var systems where the SVC directs mechanical switching) is difficult. CAPS with thyristor control does not appear attractive unless valve costs greatly decrease so that the coupling transformer becomes a dominant part of SVC cost. Even then conventional SVCs may be connected to autotransformer tertiaries.

For wide use, CAPS with thyristor control would have to be economical at lower reactive power and voltage ratings than used in the above examples.

II.3. Delta-star switching

II.3.1. Background

Typically three phase circuits are connected in delta or star. If the same three-phase circuit were arranged to operate in either delta or star connection, the ratings of the circuit would be different. Figure II.14 shows a conventional and straightforward switching arrangement that permits operation of a three-phase circuit, with impedance Z per phase, in delta or star configuration. When switches designated S_d are closed and switches designated S_s are open, the circuit is connected in delta. If the switches S_d are open and switches S_s are closed, the circuit will be connected in star. If the phase to neutral applied voltage v_a, v_b and v_c have an rms value of V volts, the voltage stress v_d and the volt-ampere rating P_d in the case of delta connection would be:

$$v_d = \sqrt{3}V / Z \text{ volts per ohm}$$

$$P_d = 9V^2 / Z \quad \mathrm{P_d}$$

The voltage stress v_s and volt-ampere rating P_s for the star connection would be:

$v_s = V / Z$ volts per ohm

$P_s = 3V^2 / Z$

The changes in voltage ratings for the delta and star connection would be:

$$\frac{v_d}{v_s} = \sqrt{3}$$

$$\frac{P_d}{P_s} = 3$$

An arrangement that gives two ratings for the same bank could be useful in certain circumstances. One application would be to increase the active or reactive power rating of the circuit when there is significant variation in applied voltages. A circuit connected in star may be reconnected in delta to offset the reduction in power or reactive power due to drop in applied voltage. Another application would be to tap the temporary overload ratings of equipment to cope with some temporary condition in the power system with or without change in the applied voltages. For example, during a disturbance in the power system, it may be possible to beneficially vary the reactive power output of a capacitor bank since capacitors typically have significant short term overvoltage capability.

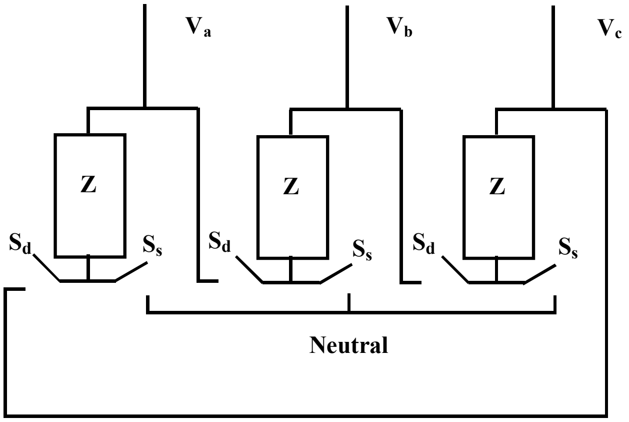


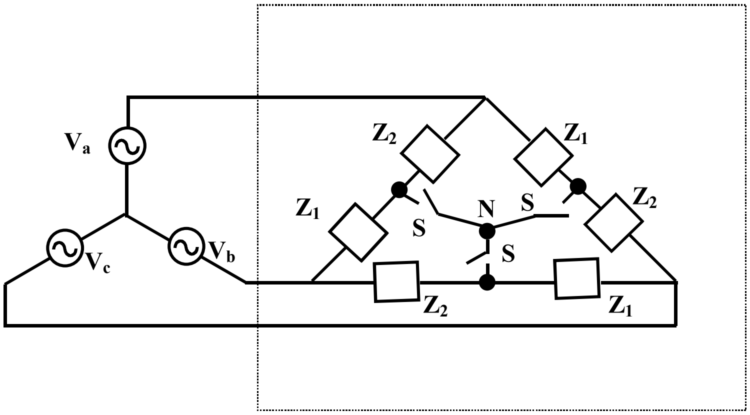
Figure II.14: Conventional delta-star switching

The conventional method shown in Figure II.14 has a number of drawbacks. It needs a large number of switches with relatively high voltage ratings. Also the changes in voltage stress on the impedance elements and volt-ampere ratings between the two connections are too large for many practical applications. A more modest change in the voltage stress and volt-ampere rating would have better scope for practical application. The method also requires that the bank be temporarily disconnected during the changeover from one connection to the other. This could have objectionable system impact. For example in switching a capacitor bank with two ratings, Q1 and Q2, Q2 being higher than Q1, the maximum switched block will be Q2, with corresponding system voltage change.

Comparing this with two banks with ratings of Q1 and (Q2-Q1), for which the maximum switched block will be only Q1 or (Q2-Q1), this voltage change will be higher, and possibly objectionable. The proposed method overcomes these drawbacks [11].

II.3.2. Detailed Description of the Method

The new method applies to circuits where the impedances in each phase can be split into two parts. This is easier to accomplish when the impedances are made up of modular units such as in high voltage capacitor banks. In the delta connection the two impedances are connected in series and, in the star connection the two impedances are connected in parallel. Both these changes - delta connection to star connection and series connection to parallel connection - are accomplished simultaneously by the single operation of three switching devices. The number of switches can be reduced to two if the neutral of the star connected circuit is isolated.



The method can be explained with the aid of Figures II.15(a) and II.15(b). For ease of presentation, the method is first discussed as it applies to a symmetrical three phase circuit. However, the method is applicable to any three phase circuit in which the impedances per phase can be split into two.

Figure II.15 (a) Delta connection realized by the new switching method

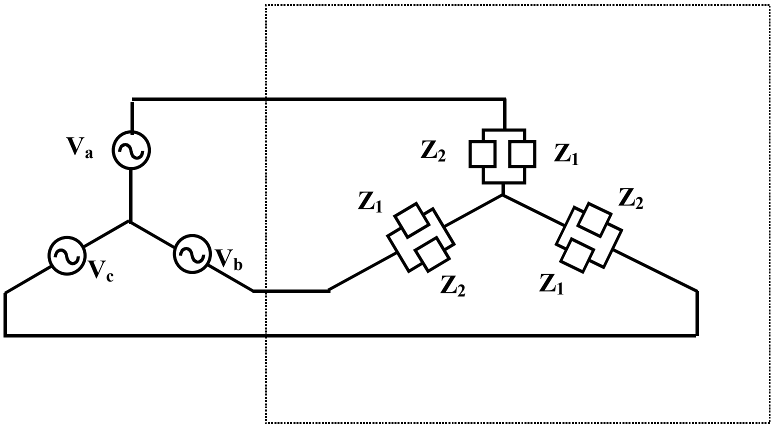


Figure II.15 (b) Star connection realized by the new switching method

Figure II.15(a) shows a symmetrical three-phase circuit in which the impedances per phase are in two parts, Z_1 and Z_2. There are three switches, one terminal of each connected to a common point designated N. The other terminals of the three switches are connected to the three nodes connecting Z_1 and Z_2 of each phase.

When the switches are in open position, the three phase circuit is connected in delta with Z_1 and Z_2 connected in series. When the switches are in closed position, the three phase circuit is connected in star with Z_1 and Z_2 connected in parallel and N as the neutral point. This is shown in Figure II.15(b).

The impedance between phases for delta connection is (Z_1+Z_2). The impedance for the star connection is $Z_1Z_2/(Z_1+Z_2)$. For the same external applied voltage, the changeover from delta to star changes the voltage stress on the impedances and the their volt-ampere rating. If the rms value of the applied phase to neutral voltage is V, the voltage stress on the impedance for delta connection, v_d, is

$$v_d = \frac{\sqrt{3}\, V}{Z_1 + Z_2} \text{ volts per ohm}$$

For the star connection, the voltage stresses on the impedances would be v_{s1} for Z_1 and v_{s2} for Z_2.

$$v_{s1} = \frac{V}{Z_1} \text{ volts per ohm}$$

$$v_{s2} = \frac{V}{Z_2} \text{ volts per ohm}$$

If Z_1 and Z_2 are equal, v_{s1} and v_{s2} will be equal and,

$$v_s = v_{s1} = v_{s2} = \frac{2V}{Z_1 + Z_2} \text{ volts per ohm}$$

In this case, the voltage stress on all impedances in the star connection will be $\frac{2}{\sqrt{3}}$ (=1.155) times that for the delta connection. This is a much more moderate increase in voltage stress than that for the method shown in Figure II.14.

If P_d and P_s are the volt-ampere ratings for delta and star connection respectively,

$$P_d = \frac{9V}{Z_1 + Z_2}$$

$$P_s = 3V^2 \frac{(Z_1 + Z_2)}{Z_1 Z_2}$$

The ratio of the voltampere ratings for the two connections is

$$\frac{P_s}{P_d} = \frac{(Z_1 + Z_2)}{3Z_1 Z_2}$$

For the case of Z_1 and Z_2 are similar impedances and if we denote Z_1 = k Z and Z_2 = (1-k) Z , where Z = Z_1+Z_2 and k a positive constant less than 1,

$$\frac{P_s}{P_d} = \frac{1}{3k(1-k)}$$

P_s/P_d is a minimum when k=0.5 or when Z_1=Z_2. When k=0.5,

$$\frac{P_s}{P_d} = \frac{4}{3}$$

Since the minimum value of P_s/P_d is 4/3, unlike the conventional method of star-delta switching, the voltampere rating for the star connection is always higher. Furthermore, the arrangement according to proposed method allows a more moderate change in the ratings between the delta and star connections.

The change in the voltampere ratings can be increased by changing the value of k. However, when k is different from 0.5, the voltage stress on Z_1 and Z_2 will be different, higher for the impedance with the smaller value. Designating Z_1 as the impedance with the lower value, the maximum voltage stress for star connection, v_s, is

$$V_s = \frac{V}{kZ} \text{ volts per ohm}$$

The method is not subject to any constraint on the nature of the impedance Z_1 or Z_2. They could be resistive, inductive or capacitive or any combination of these. As a method of controlling the reactive power, the circuits of interest here are those in which the Z_1 and Z_2 are reactive elements.

When the impedances are of different types, for example, Z_1 inductive and Z_2 capacitive, the changeover from delta to star results in a change in the type of impedance, i.e., the net impedance will change from inductive to capacitive or capacitive to inductive when the configuration changes between star and delta.

The method applies whether the neutral of the star connection is isolated or has an external connection to another circuit or ground. When the neutral of the circuit is isolated, an alternate arrangement would be to replace one of the three switches to the neutral by direct connection between the neutral and the node to which the replaced switch was connected.

This arrangement is shown in Figure II.16. If the neutral point is to be connected to an external circuit or ground in the circuit shown in Figure II.16, it can be done through a switch which remains open in delta connection and closed for the star connection.

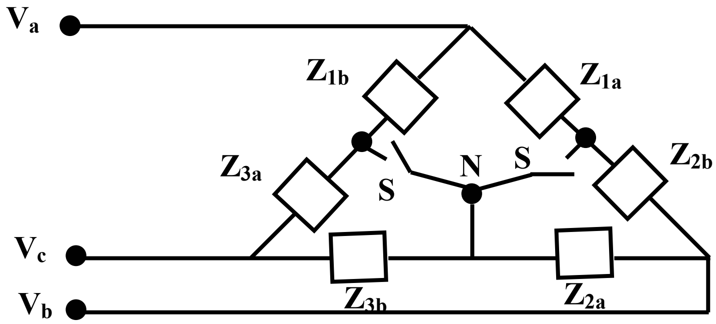


Figure II.16 Delta-Star Switching with two switches

The switches used to effect delta-star switching could be mechanical switches such as vacuum switches or SF6 breakers, or static bi-directional electronic switches such as back-to-back connected thyristor valves. Of particular interest here is the use of the power electronic switches with back to back connected thyristor valves.

Recognizing delta-star switching as a circuit with dual steady state ratings, it can be compared with two independent three phase banks. In both cases there are two sets of three switches. However in the arrangement with delta-star switching, the set of switches connected to the neutral circuit will have a relatively low voltage rating. This is particularly true in the case of capacitor banks for which the high voltage switches have to be rated to withstand twice the peak voltage across the capacitor due to residual charge on the capacitor after the switch is opened.

In the case of capacitor switching, there could be significant surge currents. To minimize such surge currents it may be necessary to have pre-insertion impedances, discharge impedance and/or controlled switching.

II.4 Protection

II.4.1 Introduction:

Computer relaying: In this section we will consider protection systems for various types of Thyristor Controlled Voltage Regulators. It should be noted that in all likelihood the protection will be provided by computer based relays using well-established protection principles in traditional relaying systems. It is therefore well to summarize the main features of computer relaying systems [12] which are relevant to the subject at hand.

The relay inputs are obtained from traditional or electronic current and voltage transformers. The burden of the input circuits is quite low, and in case of electronic transducers the relay may directly obtain data samples from the transducers. For very large banks it is likely that primary, duplicate primary, local back-up and remote back-up protection systems will be employed. To the extent that this is economically justifiable, separate current and voltage transducers would be used for various protection systems.

Sampled data is obtained from voltage and current signals. Sampling rates may range from 12-128 samples per cycle of the fundamental power system frequency. The input signals must be filtered by anti-aliasing filters corresponding to the sampling rate selected. Sampling of different input channels must be synchronized, and the sampling frequency may or may not be phase-locked with the power system frequency. If the sampling clock is a fixed frequency clock, it may be synchronized with a universal time reference such as that provided by the GPS system. Such schemes provide a very convenient means for differential protection of transmission lines and other equipment.

The main relaying signal derived from data samples in all cases is the phasor of currents and voltages. In addition, phasors of harmonics may also be needed in certain protection functions. Recursive Fourier transform calculations are the most commonly used engines for phasor computation. For high speed relaying, it is necessary to remove the dc offset in fault currents before the phasors are calculated.

The block-diagram of a computer relaying system is shown in Figure II.17. The principal elements are surge filters, anti-aliasing filters, and the sampling clock, processor, and memory modules. The surge filters are required to meet the environmental standards specified in (for example) IEEE C37.90, and in IEC 255. The anti-aliasing filters band limit the input quantities to half the sampling rate chosen in order to satisfy Nyquist criterion. The sampled data are processed by the processor, and in general Fourier type digital filters are used to determine the phasors at fundamental and harmonic frequencies. The calculated phasors are then used in implementing the appropriate relaying logic. Various types of memories are necessary to facilitate the storing of relaying software, relay settings, dynamic memory, and mass storage for oscillographic purposes. The relay outputs are contact types, either electromechanical output relays, or thyristors. Similarly, when needed, the input contacts are also brought into the relaying computer.

Computer relay hardware organization

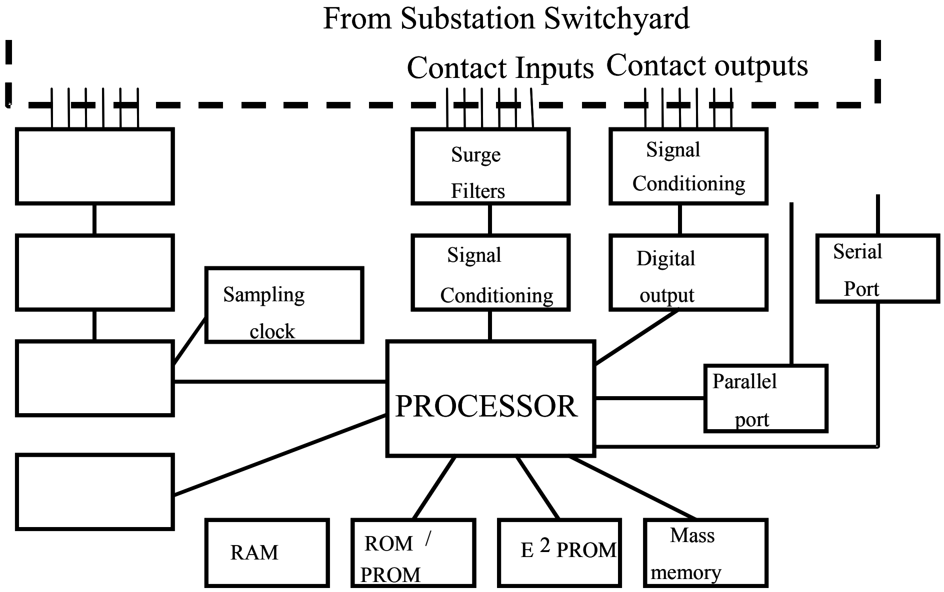


Figure II.17: Elements of a typical computer relay

Electronic and Electromechanical Relays: Although the principal protection systems will be computer based, it is likely that some back-up systems will be made up of electronic or electromechanical relays. The most likely candidates for such relays will be time-delay-overcurrent relays, directional relays, and instantaneous overcurrent relays. Protection systems employed for the Thyristor Controlled Voltage Regulators must coordinate with the back-up protection devices that are in service at remote locations.

Transducers: It is likely that normal current and voltage transformers are to be used for inputs to the protection system. Saturation of current transformers and subsidence transients in voltage transformers would need to be taken into account. It is possible that electronic (Magneto-Optic) current and voltage transformers could be available for protection systems. In this case, both of the above phenomena would not be a concern.

II.4.2 Protection Zones:

As in all protection system designs, the entire installation must be divided in overlapping zones of protection. Since we are dealing with equipment protection, the protection system employed will be differential relaying. Some protection systems will provide alarms, while others will provide tripping outputs. As in case of traditional relaying systems, reclosing may be permitted after a fault is cleared if the fault is in air-insulated region where chances of recovery are great. For all faults on equipment which is in enclosed tanks under oil, a trip will be followed by a lock-out.

As an example of zones of protection of a typical system, we will consider a Voltage Controlled Thyristor Switched Static Capacitor arrangement shown in Figure II.18. Z_1 is the transformer protection zone, Z_2 is the thyristor bridge protection zone, Z_3 is the capacitor protection zone, and Z_4 is the overall protection zone. Other types of arrangements considered in this report will be similarly divided in overlapping zones of protection.

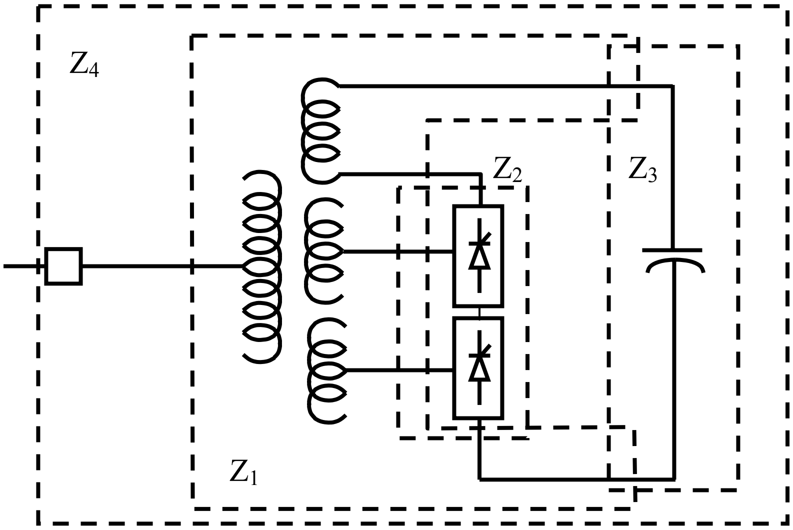


Figure II.18: Zones of protection for a VCTSC

II.4.3 Protection of subsystems of Thyristor Controlled Voltage Regulators

Transformer Protection:

Protection of transformers would be provided by traditional relays, with a few modifications as pointed out in this section. The principal protection will be harmonic restrained differential protection. Currents from multiple secondary windings could be summed before connecting to a two-winding differential relay, or each winding current may be separately used in a multi-winding differential relay. Since the protection is expected to be computer based, harmonic components could be calculated very simply by the DFT or FFT algorithms.

Anti-aliasing filters would be used before the signals are sampled. In order to estimate harmonics at least up to the 5th, sampling rate of 12 samples per cycle or greater must be used.

Percentage differential characteristic must be used, and it would be best if the prevailing winding ratio (depending upon which of the windings are conducting) should be made available to the relay in order to achieve the greatest sensitivity.

Sudden pressure relays would be used for detecting faults under oil. If the differential relay operates but not the sudden pressure relay, reclosing may be allowed depending upon the utility practice. Back-up protection would be provided by time-delay overcurrent relays. Remote back-up may also be provided by similar relays, but they must be coordinated with the differential relays and the local back-up protection.

In case of thyristor load tap changer, protection systems specifically designed for tap changing transformers would be required. If the tap position is available to the relaying logic, a more sensitive percentage differential protection could be designed.

As in case of normal transformer protection systems, it may be desirable to disable the harmonic restraint function sometime after the line side circuit breaker and switch are closed.

Special considerations: When firing angles of thyristors are variable, there must be a provision to detect errors in firing control which could lead to dc fluxing of the transformer. This could be detected in two ways: firstly by the harmonic content of the transformer current, and secondly by information from the firing angle control circuitry. For redundancy, both inputs should be used. An alarm should be sufficient; however if the condition persists for a significant length of time, the transformer may have to be tripped.

Capacitor Protection

The traditional protection for capacitors is to provide fuses in individual capacitor modules. Fuses blowing in one phase will lead to unbalance, which can be detected by unbalance voltage or current sensing depending upon the capacitor connections (wye or delta, grounded or ungrounded). Some unbalance could be tolerated without interfering with system operation. However, upon excessive unbalance, the unit must be alarmed, de-energized, and faulty capacitors replaced. A voltage transformer would be required if capacitor voltage sensing function is needed for voltage dependent relaying.

When the thermal overload capability of the capacitors is deliberately utilized, a relay using a thermal model of the capacitors would be desirable. Integrating the square of the current would provide a good indication of thermal overload in the capacitor. A good thermal behavior model of the capacitors would also take into account the recovery of the capacitors after the currents drop to below their rating.

Special considerations: If there is a possibility of harmonics being generated in the system, or if there are strong sources of harmonics in the neighborhood, special precautions must be taken to detect their presence in the capacitors in case of faults in the filters. An inversetime characteristic relay sensitive to harmonic currents in the capacitors would suffice. An alarm, followed by a trip should meet the requirements.

Reactor Protection

The traditional reactor protection systems can be used here as well. The principal protection is provided by a percentage differential relay. Oil filled reactors would have sudden-pressure relaying, with an impedance relay used for turn-turn fault. Back-up protection would be provided by a time-delay overcurrent relay. If impedance relays are to be used for turn-turn protection, voltage transformers would be required.

Bus Protection

Bus protection would be provided by traditional differential schemes. Saturation of current transformers is usually the problem in these schemes, and it is preferable to use electronic current transformers wherever they are available. It is not possible to reproduce the performance of a high-impedance bus differential scheme in a computer relay where each current is obtained separately and then summed inside a computer. The alternative of using a high sampling rate and then performing the differential relaying function before saturation sets in should be explored. If high sampling rates are deemed necessary for bus protection, it would be desirable to use the same sampling rates for all other protection systems.

Remote back-up would be provided by time-delay overcurrent or distance relays at remote terminals as appropriate.

II.5 Conclusion

Three new non-conventional methods of reactive power regulation are described in this paper. They are all well within the reach of present technology. The first one, the Voltage Controlled SVC, is a relatively simple type of SVC without harmonic filters, with potential for significant savings in equipment costs and losses. The other two, CAPS and the special type of delta-star switching, provide capacitor banks with dual ratings. If their higher second rating is based on tapping the commonly available temporary overload ratings of capacitors, they provide a relatively inexpensive means of using the capacitor banks to improve system performance during disturbances.

III. Transformer Tap Changers

III.1 Introduction

On-load tap changer (OLTC) of transformers is an important tool for proper operation of modern power systems. It enables desired voltage levels in different parts of the system despite changes in load. They were introduced in the early part of the twentieth century. The modern versions have not changed radically and are still complex mechanical devices. With the development of semiconductor devices, particularly thyristors, of relatively large current and voltage ratings, the possibility of developing static on-load tap changers is of special interest.The more common type of mechanical OLTC has two parts: a tap selector to select the tap position and a diverter to transfer the current from one tap position to another. During tap changing the load current must not be broken nor the taps be short-circuited. For this reason an impedance, a resistor or a reactor, is connected between the taps during the change over to minimize the circulating current. The tap selector and the diverter are typically oil-immersed.

The main disadvantages of the mechanical OLTC which, conceivably, could be overcome by a static OLTC, are as follows: (a) Breaking the current in the diverter leads to arcing at contacts. This leads to wear and erosion of the contacts, requiring appropriate maintenance; (b) The power loss of transition resistors is raising the oil-temperature inside the diverter switch compartment during commutations. Consequently continuous operation is normally not allowed to keep the oil-temperature within admissible limits. ; (c) Contact arcing contaminates the oil and so oil replacement is needed on the occasion of regular inspection intervals; (d) Special mechanisms have to be installed at the OLTC to prevent disastrous consequences in case of failures with regard to shafting; and, (e) The tap changer operation, though adequate for normal steady state voltage regulation, is relatively slow. The speed of the diverter switch is in the range of 50-100ms. The tap selector switch is slower and could take minutes to traverse the full tap range.

Some of the disadvantages could be overcome by the use of vacuum switches to replace the mechanical contacts in oil, either in the diverter alone or, as has been proposed, in the diverter and the tap selector. That would not improve the speed of operation to the extent a fully static tap changer could provide. However, thyristor substitution of the mechanical contacts of the OLTC has its own problems. These problems and other related issues are discussed next.

III.2 Thyristor Substitution of Mechanical Contacts

III.2.1 Commutation Problem

The problem can be explained with the aid of Figure III.1. Consider the case when thyristor A2 is conducting and the tap position is to be changed from n to n+1. The load current, I_L, is lagging the voltage U by an angle ϕ. To transfer the current from thyristor A2 to B1, sometime between t_1 and t_4, A2 is blocked and B1 deblocked. At t_4, the current through A2 becomes zero and B1 starts conducting the load current. After the A2 current becomes zero, it still needs a certain time, the turn-off time, before it can regain its capability to block the forward voltage. However, when B1 starts conducting, the voltage across A2, U_a, is in the forward direction. Applying the forward voltage before the elapse of the turn-off time results in the conduction of A2 again. This results in a short circuit across the tap changer winding between n and n+1 and failure of commutation.

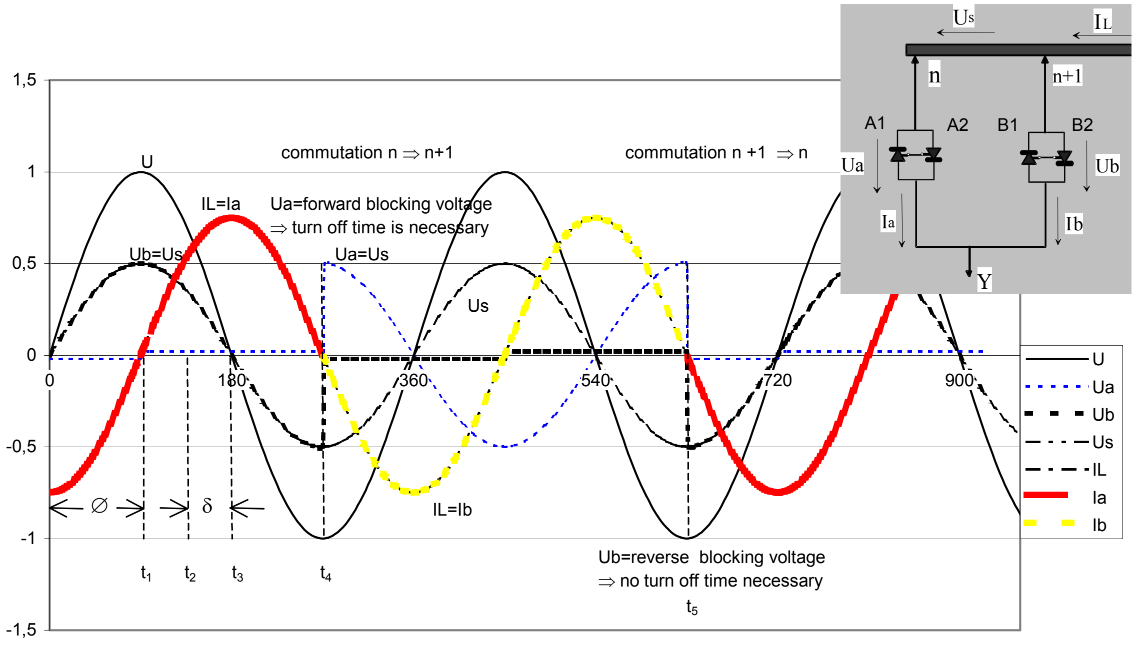


Figure III.1: Commutation in Thyristor OLTC

Under the same voltage and current conditions, commutation from n+1 to n would not be a problem. As shown in Figure III.1, when B2 stops conducting at t_5 to transfer the load current to A1, the voltage across B2 is in the reverse direction. Then there is no risk of B2 conducting again to precipitate any short circuit across the tap changer winding.

This commutation problem is related to the power factor angle. From Figure III.1, it can be seen that if the load current is leading by an angle greater than the turn-off time, δ, the commutation from n to n+1 would be successful. However, in that case, the commutation from n+1 to n would not be successful.

One way to solve this commutation problem is to delay deblocking the incoming valve by the turn-off time after the current zero in the outgoing valve. During the interval between the time the outgoing valve has ceased conduction and the time the incoming valve has started conduction, an alternate path for the load current to flow should be provided. This could be a capacitor or a series L-C circuit. Such commutating L-C circuit is shown in Figures II.1.

There is a different way to effect commutation. For the voltage and current conditions shown in Figure III.1, tap changing from n to n+1 can be accomplished by commutating the current from A2 to B2 instead of B1. For this the commutation should be initiated and completed between t_1 and t_2. In this case, the current through A2 will be forced to zero by the commutating voltage U_s with an overlapping period of conduction in A2 and B2 in a manner similar to commutation in ac/dc converters. However, when one considers the entire range of possible phase difference between the voltage and current, the risk of commutation failure is there for this type of commutation also. In general, commutation at or near the natural current zero of the sine wave is to be preferred.

III.2.2 Losses

Compared to mechanical contact switches, the losses in thyristor valves would be significant. Typically the voltage across a thyristor would be of the order of two volts. Since the losses increase proportionately with the number of thyristor levels in series, there is every incentive to minimize series connection of thyristors, as well as to limit the number of thyristor valves in the tap changer through which the load current flows.

III.2.3 Fault Current Rating

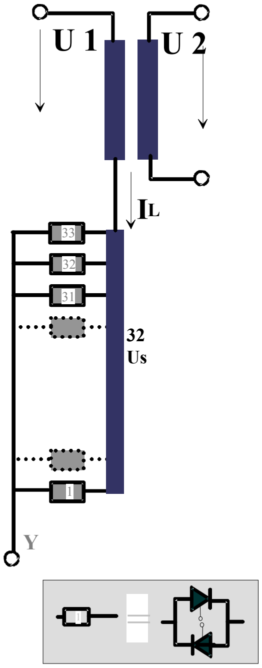
Concerns had been raised in the past about the fault current capability of the thyristors for tap changer application. However, this seems to be rather a problem of unrealistic test requirements than a real technical problem. Current standards for tap changers require it to be tested for faults for a duration of 2.5 seconds [13]. That would be a severe duty on thyristors. There does not seem to be a real system need for fault current capability of such a long period. Assuming that the back-up breaker clears the fault, the duration of the fault is not likely to exceed 8-9 cycles. 125-mm diameter thyristors with surge current rating of 100 kA peak for 8-9 cycles are currently available. If necessary, a solid state crowbar, which serves to conduct short circuit currents, could be installed. This device would allow meeting the requirements of OLTC-standards without the need of undue ratings of all thyristors.

III.2.4 Tap Changer Location

In the case of mechanical tap changers, the preferred location of tap changer is the neutral end of the higher voltage winding. The diverter duty is minimized with the lower current on the high voltage winding. In the case of mechanical contacts in oil, the higher dielectric strength needed for the higher voltage stresses resulting from choosing the high voltage winding can be obtained without significant cost penalty. In the case of thyristor tap changers, the voltage stresses would be the dominant consideration in determining the number of thyristors. From this point of view, in most cases, the preferred location of thyristor based tap changers would be the lower voltage winding. In the case of autotransformers, the obvious choice of tap changer location is the neutral end.

III.2.5 Number of Thyristors

Figure III.2 shows a tap changer arrangement for $\underline{+}$ 16 steps, assuming all the mechanical contacts are replaced by thyristors. The voltage stress across each of the thyristor valves depends on its tap position. The valves at the end, 1 and 33, will have the maximum steady state voltage stress, while the middle one, 17, will have the lowest. The maximum voltage across the other valves will vary, increasing progressively with the distance of the tap from the middle one. If the rms value of the step voltage is $U_{S,}$ the sum of the steady state voltage stresses on the all the back-to-back connected thyristor valves in one phase of the tap changer with 32 steps will be approximately 800U_S. If the step size is in the range 0.5 to 1.0 kV, as a minimum, the number of thyristors needed for the tap changer should have a total voltage withstand capability of 2,400 to 4,800 kV. At 2kA rating, so many thyristors will be enough to build thyristor valves for 1,000 to 2000 MW ac-dc converter. Clearly, the cost and physical size of the required valve assemblies will be prohibitive.



33 pairs of thyristors

Thy 1 blocks 32 Us
Thy 33 " 32 Us
Thy 17 " 16 Us

Figure III.2: Thyristor Substitution of Mechanical Contacts in Tap Selector of OLTC

It can be concluded that an all-static thyristor OLTC in which thyristors replace mechanical contacts of the conventional OLTC is not a viable practical proposition. Alternative solutions pursued fall into three types: (1) Hybrid OLTCs with thyristor assisted diverter switch; (2) Hybrid OLTCs with GTO-assisted diverter switch; and, (3) Fully static OLTCs with thyristor switched tap changer windings.

III.3 Hybrid Thyristor-type OLTC

III.3.1 Basic Concept:

The hybrid thyristor-type OLTC consists of a thyristor-type diverter switch and a mechanically operated tap selector. The thyristor-type diverter switch is generally equipped with several mechanical auxiliary switches, such as: (a) Shunt contacts in order not to dimension the thyristors for short circuit current and to reduce losses on the operating positions; (b) Contacts connected in series before the thyristor valves to eliminate the transient voltage stresses occurring in the step winding; and, (c) If necessary, additional changeover switches to minimize the number of thyristors and to effect commutation of the load current first to a transition resistor and then to disconnect the circulating current through the transition resistor by one back-to-back connected thyristor valve.

Generally, there are two different arrangements:

1. Hybrid thyristor-type diverter switch commutating without transition resistor (Figure III.3)
2. Hybrid thyristor-type diverter switch with transition resistor (Figure III.4)

III.3.2 Hybrid Thyristor-type Diverter Switch without Transition Resistor:

As is shown in Figure III.3 the diverter switch of a commutating diverter switch without transition resistor operates – without the circulating current across a transition impedance, which is typical for an OLTC – by directly commutating the load current from the thyristor path of the current carrying diverter switch side (e.g.: n) to the thyristor path of the pre-selected diverter switch side (e.g.: n+1) at current zero.

In the following, a switching operation from n to n+1 is explained in detail (Figure III.3):

At the time t1, the isolating contact H2 closes, which connects the blocked thyristor pair T2 to the step voltage. The trigger generator triggers thyristor group T1 that takes over the load current after the opening of the shunt contact D1 at t2.

At t3, the control contact EG switches to EF so that the thyristor group T1 receives no more trigger pulses.

Until the next current zero the load current is flowing across group T1 that blocks afterwards. The trigger pulses are not set free for thyristor group T2 until the voltage sensor at T1 has measured a voltage rise (an indicator for the proper interruption of the current across T1) and the turn-off-time of the thyristors T1 has passed. It is necessary to wait for the turn-off time to pass, because the breaking thyristor in T1 is subjected to voltage stress in the blocking direction after T2 has been triggered.

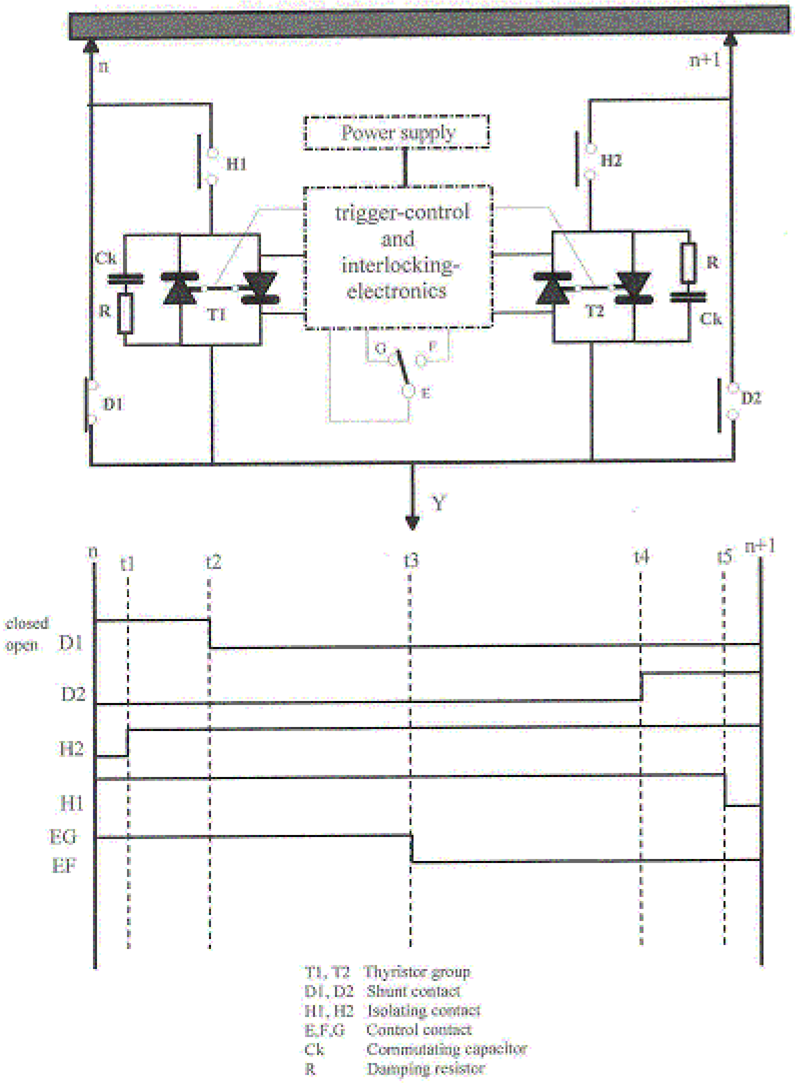


Figure III.3: Hybrid thyristor-type diverter switch without transition resistor

In the period between the quenching of T1 and the triggering of T2 no thyristor path is available for carrying the load current. The so-called commutating capacitors, C_k, each of which connected in parallel to the respective anti-parallel thyristor group, are thus taking over this task.

The shunt contact D2 closes at t4 and takes over the load current of the thyristor group T2.

The isolating contact H1 is opened at t5, disconnects the thyristor group T1, and the trigger generator stops the emission of trigger pulses for T2. The thyristor path T1 is therefore not under voltage stress and the diverter switch operation is completed.

The function of the commutating diverter switch requires components that are not suitable for operating in hot insulating oil, in particular: (a) Interlocking electronics to prevent simultaneous triggering of both thyristor paths, thus preventing a short-circuit between steps to occur; (b) Measuring equipment for measuring the voltage increase at the thyristor groups after they have entered into their blocked state; and, (c) Commutating capacitors

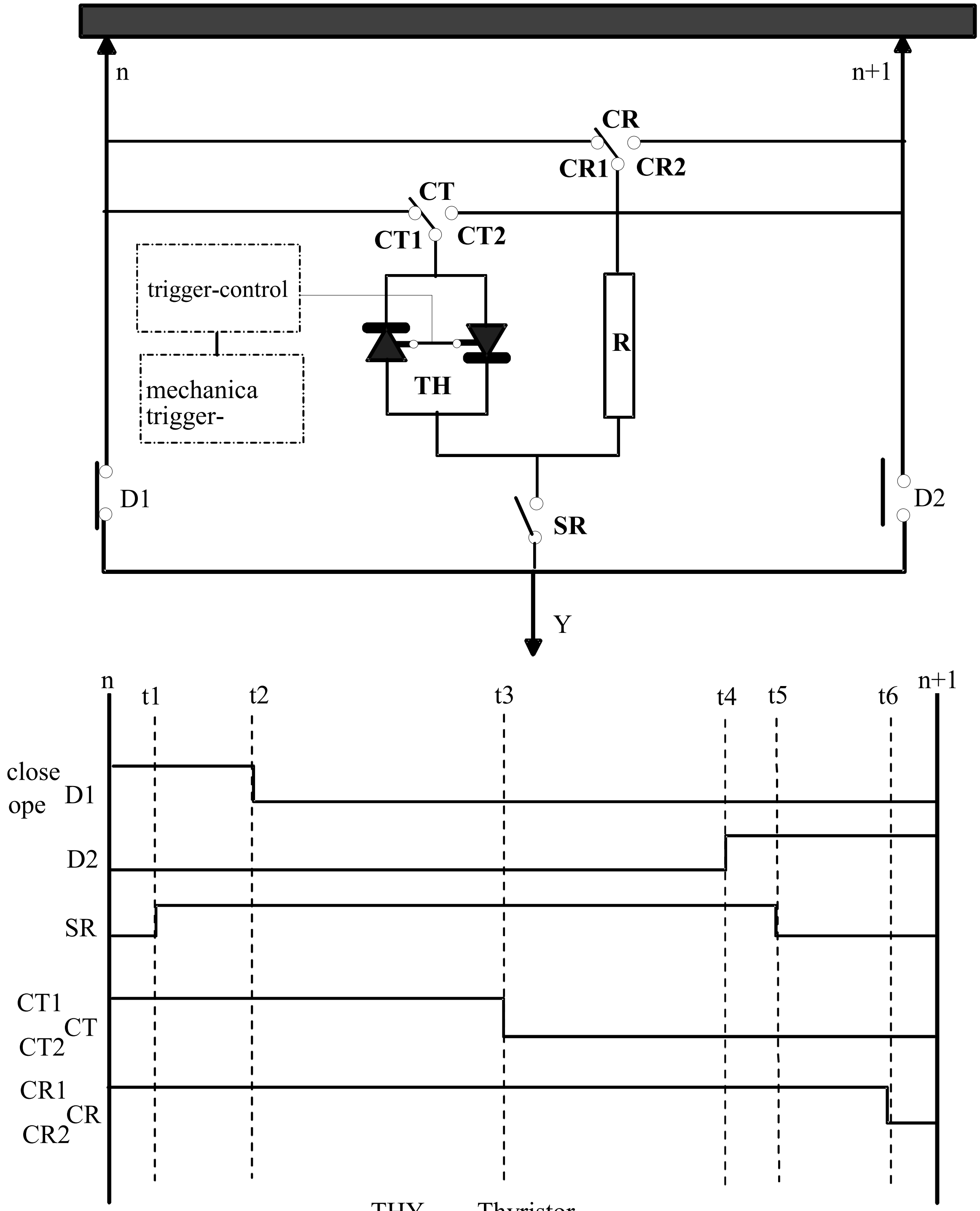
Consequently, the commutating diverter switch will not be designed like a conventional diverter switch for transformer in-tank installation, but as so-called bushing-type, where the power electronics and the control electronics are located in a separate waterproof housing placed on a bushing insulator. The leads to the diverter switch run inside the bushing to an insert mounted underneath the bushing and comprising the current-transferring sliding contacts as well as the mechanical shunt contacts and the isolating contacts. This insert is installed in a diverter switch oil compartment as is in the case of conventional OLTCs.

In total the commutating diverter switch is very long, which is due to the serial arrangement of the electronics housing, the duct and the insert with mechanical switches. This makes the handling during installation and de-installation (e.g.: for revisions) correspondingly difficult.

III.3.3 Hybrid Thyristor-type Diverter Switch with Transition Resistor

This type of hybrid thyristor-type diverter switch can be designed in a much simpler way, particularly the interlocking electronics and the commutating capacitors can be omitted.

Figure III.4 illustrates the connection diagram of a hybrid thyristor-type diverter switch with transition resistor. It is a basic connection diagram with only one anti-parallel thyristor pair performing a transfer switching operation by first commutating the load current to the transition resistor and in the second switching process interrupting the circulating current flowing across the resistor. In the following, a diverter switch operation from tap n to tap n+1 is explained in detail:



THY	Thyristor
D1, D2	Shunt
SR	Auxiliary
CT	Auxiliary
CR	Auxiliary
R	Transition

Figure III.4: Hybrid thyristor-type diverter switch with transition resistor
Connection diagram and switching sequence

In Figure III.4, initially the load current flows from the regulating winding tap n across the main contact D1 to the star point Y.

- The switching operation starts with the closing of the auxiliary contact SR (t1), which is not under load
- The thyristors are triggered
- The main contact D1 is opened (t2) so that the load current commutates onto the low-Ohm path CT1-THY-SR
- The thyristors do not receive any more trigger pulses, so that they are blocking after the next current zero, and the load current commutates to the high Ohm resistor path CR1-R-SR
- The mechanical changeover switch CT switches from CT1 to CT2 under no load conditions (t3)
- The thyristors again receive trigger pulses. The load current now flows from the regulating winding tap n+1 across CT2-THY-SR to the star point Y. In addition, a circulating current flows between tap n and n+1 across the path n+1-CT2-THY-R-CR1-n. The step voltage drives this circulating current and the transition resistor determines its value.
- D2 closes (t4) while being under almost no voltage stress, and takes over the load current.
- SR opens under no-load condition (t5)
- The thyristors do not receive any more trigger pulses, so that they block from the next current zero on and disconnect the circulating current.
- The changeover switch CR is switched from position CR1 to position CR2 under no-load conditions (t6).

Thus, the new operating position connected with the regulation tap 2 is reached.

The maximum allowable top-oil temperature for long-time emergency loading according to the IEC 354 standard for oil-immersed transformers under load is 115 °C. The difference of 10 K between this and the maximum junction temperature of the thyristors of 125°C is not sufficient to cover the self-heating of the thyristors in case of an emergency. Especially under these operating conditions frequent switching operations by the OLTC under overload conditions is necessary due to the network. Thus there is a risk of the thyristors being heated up to the temperature range of the maximum junction temperature or even beyond it. Hence, in practice the drive of the hybrid thyristor-type diverter switch with transition resistor is electronically blocked when the temperature of the insulating medium in the diverter switch oil compartment measured by a temperature sensor reaches a certain limit that is clearly below the top-oil temperature limit of 115°C required by the IEC 354 standard for long-time emergency loading.

III.3.4 Comparison of Hybrid Diverter Switch with and without Transition Resistor

Table III.1 shows the advantages and disadvantages of the respective concept of commutating diverter switches as opposed to thyristor-type diverter switches with transition resistors in detail. The thyristor-type diverter switch with transition resistor can be realised in the design and size of a conventional OLTC for in-tank installation.

Table III.1: Comparison of different hybrid thyristor-type OLTCs

Concept	**Hybrid thyristor-type OLTC as direct commutating type without transition resistor (Scheme Figure III.3)**	**Hybrid thyristor-type OLTC with transition resistor (Scheme Figure III.4)**
Advantages	No heating up of the insulating medium by transition resistor. Unlimited number of consecutive switching operations is possible. Remark: This performance can be likewise be achieved by those conventional OLTCs with vacuum interrupters that are designed for the use of transition reactors instead of transition resistors.	Diverter switch can be designed with only one anti-parallel thyristor pair, if a sufficient number of auxiliary switches are provided for. Easy firing electronics possible No interlocking electronics required No commutating capacitors required Suitable for the use in hot insulating liquids Suitable for in-tank installation Compact design and easier handling than bushing-type
Disadvantages	At least 2 anti-parallel thyristor groups required An additional outdoor-proof housing must be provided For preventing short-circuits between steps the firing electronics of both thyristor groups must be electronically interlocked. During the turn-off time the load current has to flow across space demanding commutating capacitors Special electronic components only suitable for operation in air	Transition resistor required The temperature increase of the insulating medium which is caused by the transition resistor may endanger the blocking ability of the thyristors at high initial temperature levels. The number of successively performable switching operations is thus limited based on the initial thermal situation.

III.3.5 Comparison of the hybrid thyristor-type OLTC with conventional OLTCs

Hybrid Thyristor-type OLTC versus Mechanically Operating OLTCs with Arc-producing Switching Operations in Oil*:*

The high number of mechanical elements in the diverter switch, and the conventional design of the tap selector subject the hybrid thyristor-type OLTC to the same limitations that apply to conventional, purely mechanically operating OLTCs. Hence there are no substantial differences in regard to regulating rate and permissible switching frequency.

On the other hand, owing to the thyristors taking over the switching function, with the absence of arcs, the hybrid thyristor-type OLTC offers operating advantages: (a) No carbonised oil; (b) No contact erosion due to arcing; and, (c) Possibility to use alternative insulating media.

These features mean in particular lower maintenance works than for conventional OLTCs operating in oil. Considering the higher purchase costs, it is disputable, whether or not there is an advantage of the hybrid thyristor-type OLTC with respect to the total cost of ownership over the life of a transformer.

Since neither the total life of a hybrid thyristor-type OLTC determined by the tap selector nor the switching performance (operating speed, operating frequency) deviate from those of a conventional OLTC, the two switching technologies only differ in as far as their application spectrum is concerned: the hybrid thyristor-type OLTC – like the OLTC with vacuum interrupters – is principally better qualified for use in alternative insulating media.

However, the question of long-term behaviour of a number of electronic and power electronic components in the various alternative insulating media, especially at high temperatures, presents a special technical challenge. This challenge is also represented in the fact that the thyristor-type diverter switch insert generally – in contrast to the conventional OLTC or the OLTC with vacuum interrupters – cannot be subjected to the vapour phase drying procedure while inserted in the transformer.

Hybrid Thyristor-type OLTC versus OLTC with Vacuum Interrupters

The hybrid thyristor-type OLTC and the OLTC with vacuum interrupters would be put into the same regulating category, when it comes to regulating performance. The following basic features apply to both switching technologies: (a) No carbon by-products; (b) Possibility to use alternative insulating media; (c) No contact wear (hybrid thyristor-type OLTC), or, no substantial effects of the contact wear on the life of the OLTC or the maintenance intervals (OLTC with vacuum interrupter).

As the detailed comparison of hybrid thyristor-type OLTCs (for in-tank installation with transition resistor) to OLTCs with vacuum interrupters in Table III.2 shows, there is no significant disadvantage of the OLTC with vacuum interrupter to the hybrid thyristor-type OLTC. On the contrary, the vacuum switching technology has clear advantages in regard of the following points: (a) Max. step voltage; (b) Max. step power; (c) Long-term resistance in alternative insulating media; (d) Overall complexity; (e) Risk of failures; (f) Extent of operating experience; and, (g) Procurement costs.

The hybrid thyristor-type OLTC as commutating switch without transition resistor offers the possibility of unlimited number of consecutive switching operations**.** In this respect, it is surely superior to the hybrid thyristor-type OLTC with transition resistor (in-tank type) or the OLTC with vacuum interrupters. However, because of a number of serious disadvantages detailed in Table III.1, its use is only for special applications where the ability to perform a very high number of successive switching operations is very useful. As a result, the hybrid thyristor-type OLTC as commutating switch without transition resistor is not considered in the comparison with OLTC with vacuum interrupter in Table III.2

Table III.2: Comparison hybrid thyristor-type OLTC versus OLTC with vacuum interrupters

	Hybrid thyristor-type OLTC for in-tank installation with transition resistor	**OLTC with vacuum interrupters**
Max. operating speed	Determined by the tap selector, principally no difference to conventional OLTCs	
Max. Operating frequency (no. of operations per hour)	Is determined by the power loss of the transition resistors and the maximum permissible junction temperature of the thyristors. Because of the self-heating of the thyristors, the maximum permissible oil temperature in the diverter switch is below the permissible junction temperature.	Is determined by the power loss of the transition resistors and the maximum permissible diverter switch oil temperature. The maximum permissible oil temperature in the diverter switch is determined by the temperature resistance of the insulating media and gaskets used, and is normally above the permissible junction temperature of standard thyristors.
Electrical life	As the thyristors are only in operation for a very short duration during the diverter switch switching operation, which is only a few half-cycles, the thyristors cannot be considered as life-limiting elements.	Is determined by the life of the vacuum interrupter, which depends on the switching current. Replacement approx. every 800.000 – 1.000.000 operations
Mechanical life	Is determined by the tap selector, principally no difference to conventional OLTCs	
Max. rated through current	The rated through currents of conventional OLTCs can principally be reached and if need be also be surpassed.	
Max. step voltage	Using 5.6 kV thyristors (Urrm): approx. 1300 V Using 8 kV thyristors (Urrm): approx. 1900 V Series connections of thyristors have not been realised so far due to the space required (in-tank installation!) and the costs.	The maximum step voltage of the conventional OLTC product range is 4 – 5 kV, which can easily be met by vacuum interrupters.

Step capacity	Due to the limited step voltage, only a part of the requirements a conventional OLTC meets can be covered.	Completely covered and option to increase the step capacity that is required of conventional OLTC product range.
Application range	Steady-state voltage and load flow regulation	
Behaviour against alternative insulating media and during the drying procedure	To ensure long-term resistance of the various electronic and power electronic components is a technical challenge. Thyristor-type diverter switch insert must be removed from the transformer prior to the vapour phase drying of the transformer.	The small number of insulating and sealing materials of the diverter switch can be checked with respect to their long-term resistance against different materials used with reasonably little work and expenditure. Removal of the diverter switch insert prior to vapour phase drying of transformer is not required.
Operational experience	A few pilot installations	Wide application in a number of OLTC product lines. Used in air as well as in oil, in high-speed resistor-type OLTCs as well as in reactor-type OLTCs.

Table III.2: Comparison hybrid thyristor-type OLTC versus OLTC with vacuum interrupters (contd.)

	Hybrid thyristor-type OLTC in-tank installation with transition resistor	**OLTC with vacuum interrupters**
Complexity	For reducing the number of thyristors used, connection schemes are applied that require several mechanical auxiliary switches. As a consequence, the mechanical complexity is no less than that of the OLTC with vacuum interrupters.	Altogether less complex, as the control electronics, the firing electronics, perhaps including a mechanically realised firing generator, and all power electronics components (thyristors + snubber circuits) are omitted.

<table>
<tr><td>Required maintenance</td><td colspan="2">The replacement intervals for the vacuum interrupters are so long (s. above) and the replacement is so easy to carry out, that the maintenance required is only determined by the mechanical parts of the diverter switch including braided leads.
Due to the known ageing behaviour of electronic components a failure preventing maintenance strategy for hybrid thyristor-type OLTCs requires a cyclic replacement of power electronics as well as control and firing electronics components during the usual OLTC operating time of 30 to 40 years.
For above reasons, the maintenance expenditure for a hybrid thyristor-type OLTC amounts to no less than that of an OLTC with vacuum interrupters.
In both cases the oil is not carbonised.</td></tr>
<tr><td>Risk of failure</td><td>A higher risk of failures is expected than for the OLTC with vacuum interrupters.
The grounds for this supposition are as follows:
- In regard to the ageing behaviour of electronic components, the requested operating time for an OLTC of 30 to 40 years seems very long, especially with a high temperature level in insulating oil. The operation risk caused by this must be prevented by means of a consequent replacement strategy.
- Electronic components are sensitive to voltage and temperature overload.
Particularly in tap-changer operation these two categories must be fully employed to ensure an adequate regulating performance.</td><td>The mechanical complexity of the vacuum interrupter is comparable to that of the hybrid thyristor switch, and with conventional OLTC designs, too. The low rate of mechanical failures gathered over many years of operation with conventional OLTCs is therefore taken as reference.
Today, the vacuum switching technology has reached a high standard after many decades of development, and it is indisputably recognized that the vacuum can be securely maintained in the tube for more than 30 years. An MTTF of more than 20,000 years that has been determined by a manufacturer of vacuum interrupters on the basis of the products delivered, and the long-term experience gained with vacuum interrupters operating in OLTCs make it likely to expect an extremely low risk of failure of the vacuum interrupter.</td></tr>
</table>

<table>
<tr><td rowspan="2">Procurement costs</td><td colspan="2">The costs for the mechanical parts of the tap selector and the diverter switch should be more or less the same for both switching technologies.
The procurement costs of thyristors and vacuum interrupters should be about the same as well.</td></tr>
<tr><td>The costs for the trigger-electronics, the control electronics and the snubber circuits of the power electronics must be added.</td><td></td></tr>
</table>

III.3.6 Conclusion:

The above comparison shows why the hybrid thyristor-type OLTC technology has only been implemented to a very small extent so far, and it can also be expected that it will not catch on to a wider extent in the future either, as the vacuum switching technology clearly offers better performance.

The quintessence of the comparison of the different switching technologies is that the combination of power electronics and mechanical switches used in the hybrid thyristor-type OLTC technology deprives the electronics of its essential strengths, such as switching speed and switching frequency. The main weaknesses of the power electronics, such as voltage strength and ageing behaviour, cause the hybrid thyristor-type OLTC technology to be in a bad position against competitive switching technologies, particularly the vacuum switching technology. This is not expected to change in the near future.

III.4 Hybrid GTO-type OLTC

The commutation problem associated with thyristor based tap changer can be overcome by the use of GTOs or IGBTs in the place of thyristors. With maximum voltage ratings of these devices lower than those of thyristors, their use to replace mechanical contacts in the tap changer would be even more costly than in the case of thyristors. Hence their use also is considered only in diverters with mechanically operated tap selector. One such laboratory-tested scheme is described below [14].

Figure III.5 shows the basic circuit of the diverter. A, B and C shown in the figure are GTO ac switches. The ac switch configurations could be a bridge circuit, of the type shown in Figure III.6. V_A and V_B in Figure III.5 are vacuum switches. The vacuum switches are driven by fast-acting actuators, which latch magnetically at either end of the travel, to hold the vacuum switch in the closed or open position without the application of a holding current. The actuator allows the unit to switch rapidly and repeatedly, giving the tap changer a fast speed. The primary diverter switch consists of these vacuum switches and the GTO switches A and B. There is also an auxiliary diverter comprising of a low power transformer of turns ratio 20:1, the GTO switch C and a 1kV varistor. The operation of the diverter to transfer the current from the tap position to which GTO switch A is connected through switch S_n to the tap position to which GTO switch B is connected through switch $S_{(n+1)}$ is as follows:

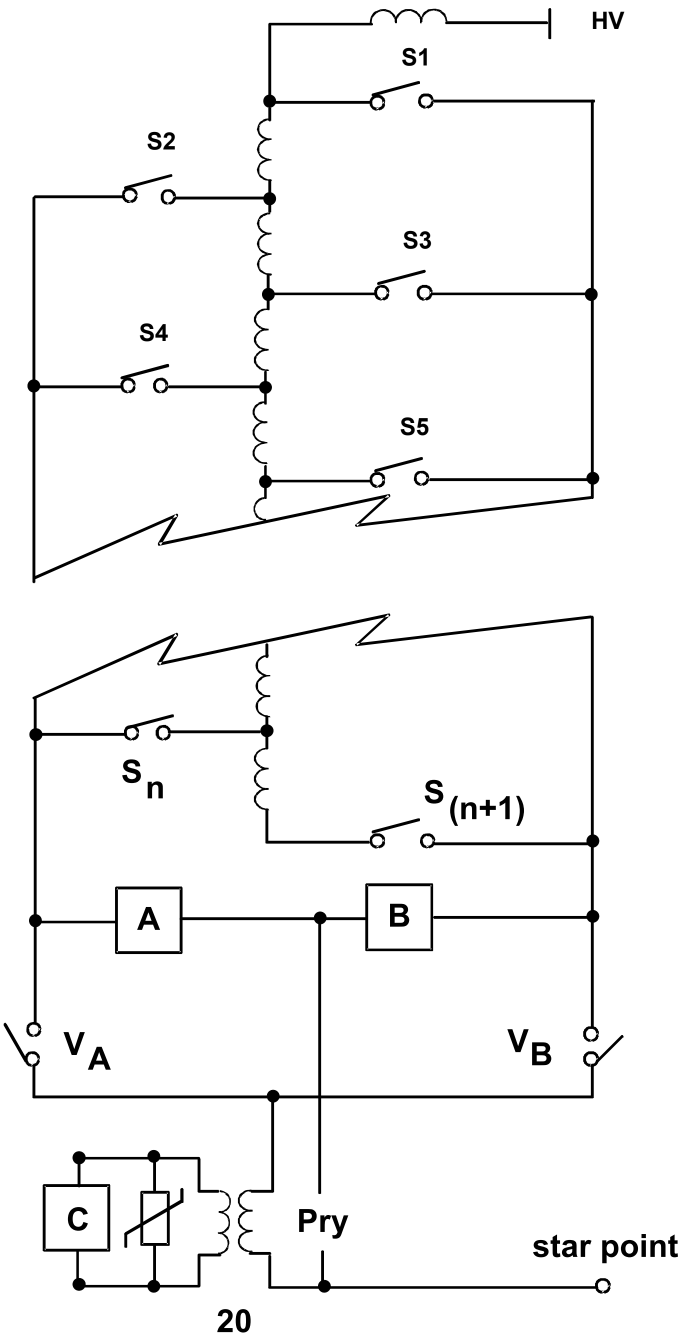


Figure III.5: GTO Based OLTC

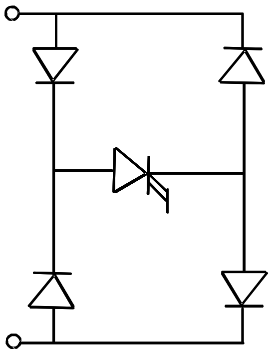


Figure III.6: GTO Switch Configuration

In steady state, vacuum switch V_A and GTO switch C conduct. The current through the vacuum switch flows through the primary of the auxiliary transformer. The current through the secondary of the transformer and the GTO switch C is one-twentieth of this current. GTO switches A and B and the vacuum switch V_B are open. The current transfer is initiated by turning off GTO switch C and turning on GTO switch A. Auxiliary transformer secondary current now flows through the varistor, causing a voltage of 1kV to appear across it. Consequently, a voltage of 50 volts appears across the primary of the auxiliary transformer. This voltage forces the phase current flowing through the vacuum switch V_A to be transferred to the GTO switch A over a period of a few microseconds, the rate of transfer being determined by the auxiliary transformer leakage inductance. When this current transfer is completed, V_A can be opened under condition of no current flow. On the next current zero, GTO switch A is turned off and GTO switch B is turned on. Following this action, the phase current flows through the new tap position and through the GTO switch B. Now the vacuum switch V_B is closed. Then the GTO switch C is turned on and the GTO switch B turned off. The current is then transferred from the GTO switch B to the vacuum switch V_B. This completes the tap changer operation.

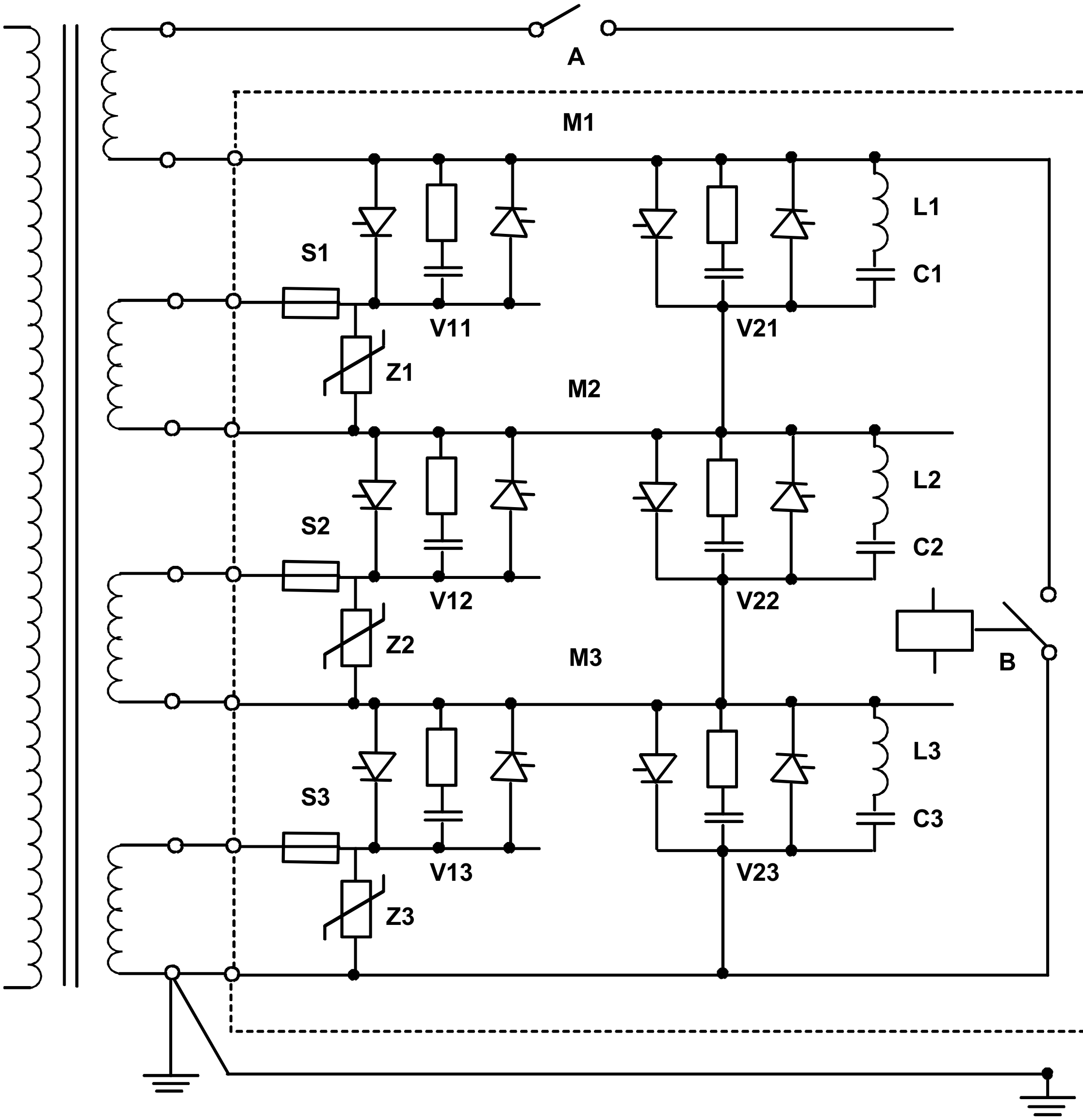
There is no inter-tap circulating current during the tap changer operation. Thus it is possible to make multiple tap jumps, provided the voltage ratings of the diverter ac switches are adequate. When carrying out multiple jumps, vacuum switches V_A and V_B need not be operated until a resting state is reached at the end of the tap change, and so the speed of tap changing is further enhanced. GTO switches A and B can be subjected to high fault current if, and only if, the fault occurs during the tap changer operation. Probability of such an occurrence is very low. Should it occur, the i^2t limit for modern GTOs is sufficient to allow survival of the GTOs, provided the current is quickly transferred to the vacuum switches. Faults are more likely to occur when GTO switch C is conducting. However, the fault current levels in GTO switch is within the capabilities of modern GTOs since it is reduced by the turns ratio of the auxiliary transformer. The failure of the GTOs switches is usually in the form of short-circuits. They are easy to detect and to take action to prevent tap-tap short-circuits. The scheme has been shown to work for all power factors and both power directions. It is claimed that a full-scale unit would be able to make multiple tap jumps and in this mode could traverse a typical 19 tap range in about 0.8 seconds.

While the particular arrangement discussed above uses GTOs, the performance of the circuit is expected to be similar if IGBT valves were to be used in the place of GTO valves.

III.5 Static OLTC with Thyristor Switched Windings

The hybrid OLTCs, thyristor assisted or GTO assisted, fail to live up to the promise of significant improvement in the speed of operation from static switching. To extend the application of OLTCs to enhance power system performance with respect to system stability or sub-synchronous resonance, it is necessary to complete tap changer operations in about one cycle.

In 1986, a fully static single phase OLTC was installed in the 16.5kV, 16 2/3Hz. systems of Norwegian State Railways [15]. Figure III.7 shows the basic circuit. The tap changer had three thyristor switched windings giving four tap positions. There are two sets of back-to-back connected thyristors per switched winding, one in series to insert the winding and the other in parallel to bypass the winding. An L-C circuit provided across the valves, along with delaying the deblocking of the incoming valves until the expiry of the turn-off time of the outgoing valves, ensures successful commutation between the series connected and parallel connected valves. There has been no reported problem in its operation over many years.



A	Main circuit –breaker
B	Bypass switch
L, C	Commutation
M	Module
S	Fast-acting fuse
V1	Series valve
V2	Parallel valve
2	2nO resistor for overvoltage protection

Figure III.7 Basic circuit the fully static single phase OLTC installed in the 16,5 kV, $16\frac{2}{3}Hz$ Norwegian state Railways System

Although this is in a distribution system, there is no reason why it cannot be applied to transmission systems of higher voltages. It should be possible to extend the concept to greater number of tap positions also. A schematic diagram of such a tap changer for 32 steps is shown in Figure III.8. Such an OLTC would have 64 back-to-back connected thyristor valves. With current thyristor technology, it may be possible to get tap range of more than 100kV without series connection of the thyristors. Even without series connection of thyristors, there are 32 thyristor valves through which the current has to flow, which could make the losses unacceptably high.

The number of switched windings can be reduced by half by arranging the connection of switched windings to add as well as to subtract their voltages to the voltage of the main winding. Such an arrangement is shown in Figure III.9. The number of thyristor valves is significantly reduced. However, the four valves, which determine whether the voltages of the switched windings are additive or subtractive, will have significantly higher voltage stress.

Another approach that gives minimum number of switched windings is to provide windings with voltage ratings which are multiples of three. This is the same arrangement described with reference to VCSVC. Such an arrangement for a tap changer is shown in Figure III.10. In this case there will be ±13 steps. In most cases this should be sufficient. With a fourth switched winding, it is possible to get as much as ±40 steps. If the number of steps is between, ±13 and ±40, the voltage rating of the fourth winding could be that which is needed to get the extra steps to the ±13 step arrangement, or, choose values of the voltages of windings to get optimally rated thyristor valves. Figure III.11 shows an arrangement for ±16 steps.

In the bridge connected thyristor arrangements shown in Figures III.10 and III.11, the commutation problem could be solved by connecting an L-C circuit across the nodes of the bridge not connected to the windings. This is explained in Section II.1.1, and shown in Figure II.1. Therefore, this is one of the arrangements with very small number of commutating circuits. Also, the thyristor valves and thyristors needed for these bridge circuits are significantly less than those for the circuits of Figures III.2, III.8 and III.9. However, since there are two thyristor valves per switched winding always conducting, the losses in these circuits will be higher.

Two other circuit arrangements for thyristor switched windings are shown in Figures III.12 and III.13. For ± 16 steps, they have fewer thyristor valves compared to the other thyristor switched winding arrangements considered. Whether the fewer valves translate into fewer thyristors depends on the step voltage sizes. They obviously have more windings also. One particular feature of the circuit of Figure III.13 is that the voltage stresses on the different valves are more uniform. That could have some cost benefit.

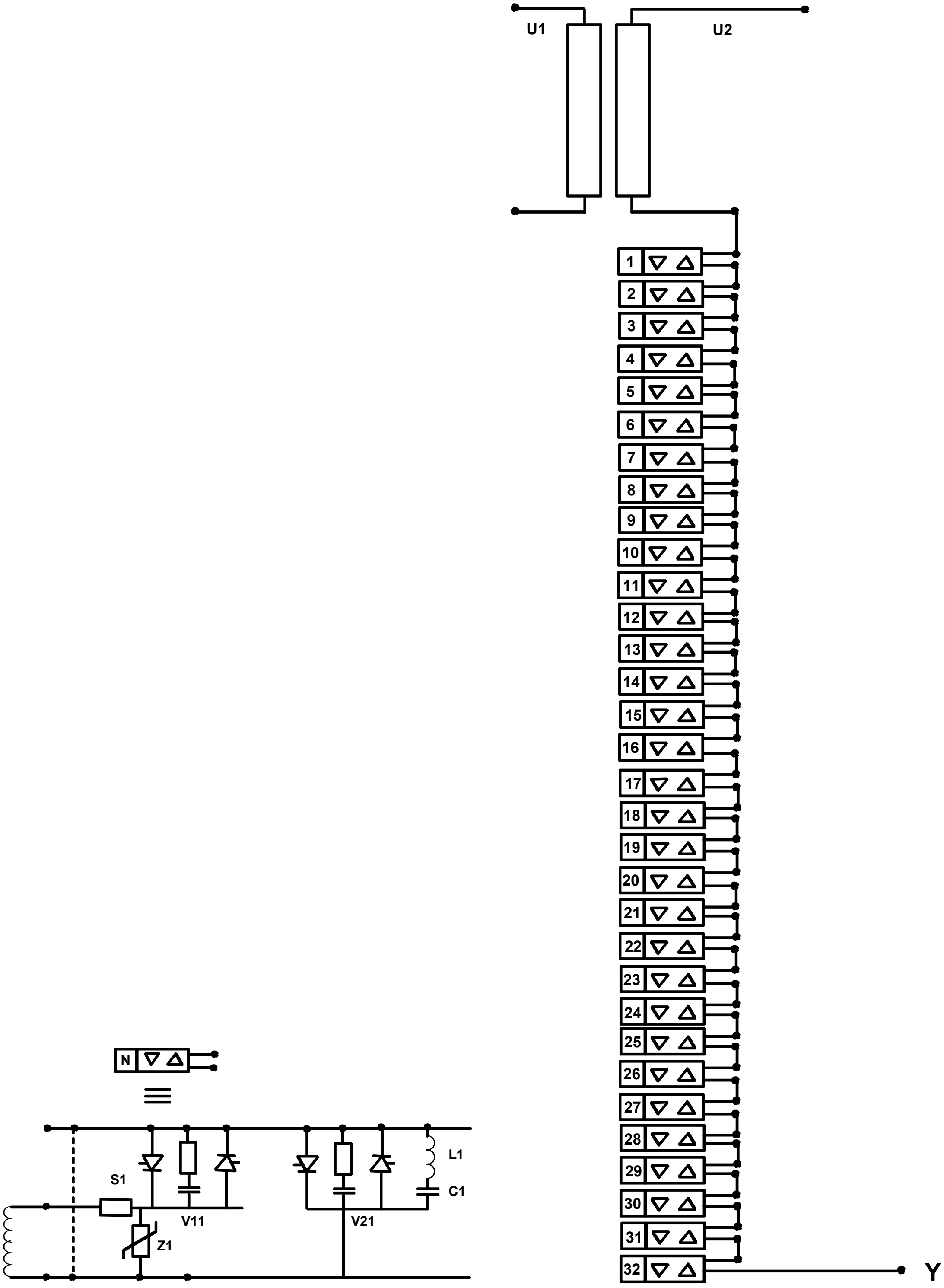


Figure III.8 Schematic diagram of tap changer for 32 steps

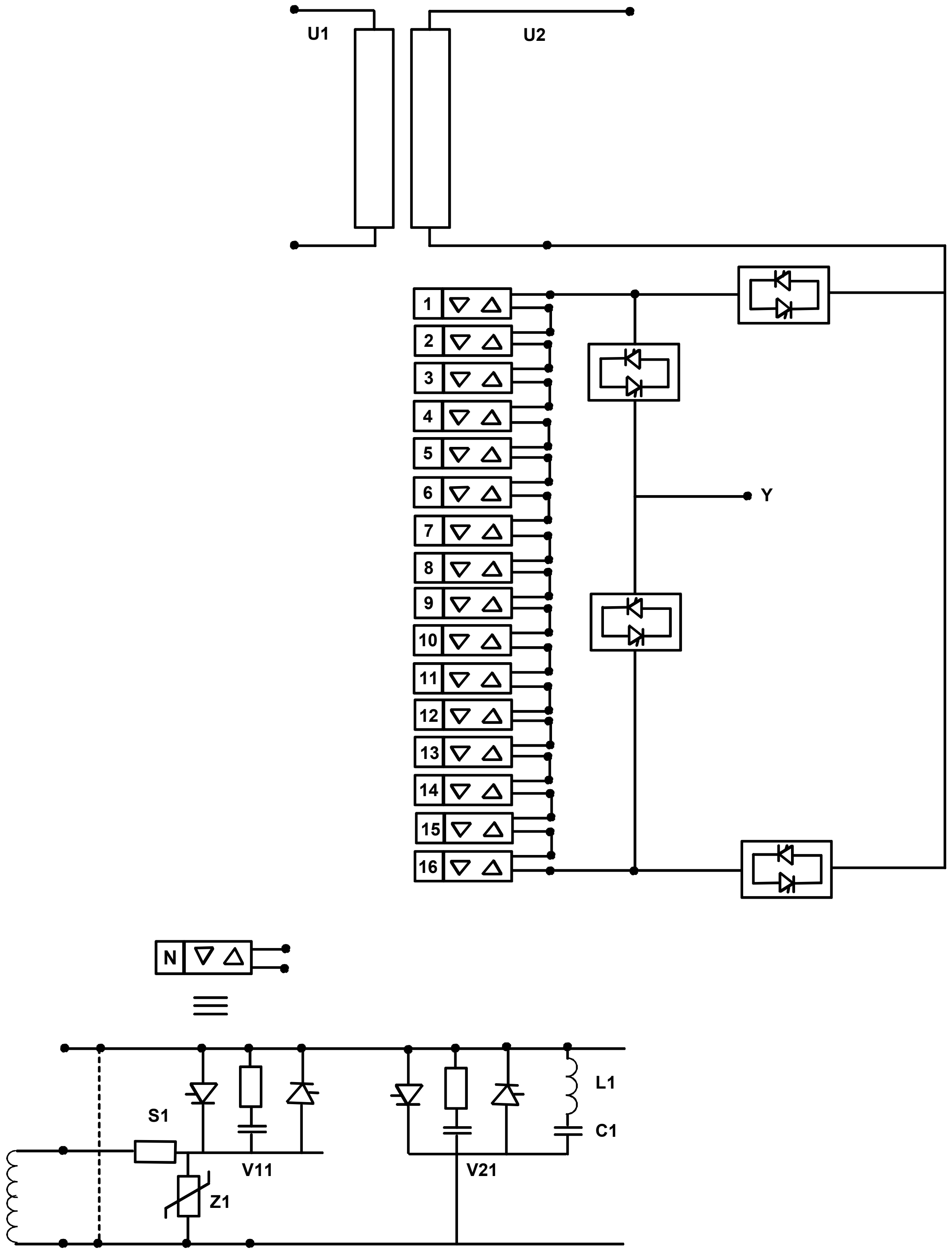
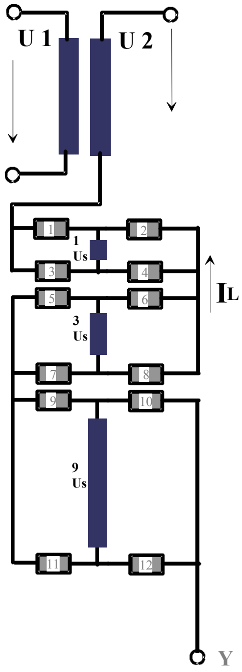


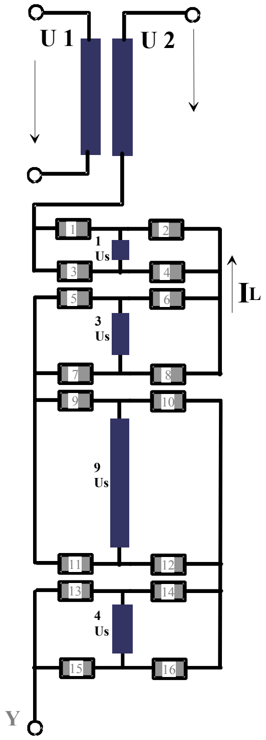
Figure III.9 Schematic diagram of tap changer for 32 steps with reduced number of thyristor valves



12 pairs of thyristors

Thy 9-12	block	9 Us
Thy 5-8	"	3 Us
Thy 1-4	"	1 Us

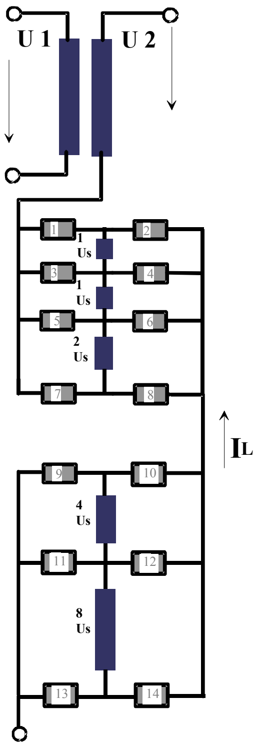
Figure III.10 Tap changer arrangement with three switched windings



16 pairs of thyristors

Thy 9-12	block	9 Us
Thy 13-16	"	4 Us
Thy 5-8	"	3 Us
Thy 1-4	"	1 Us

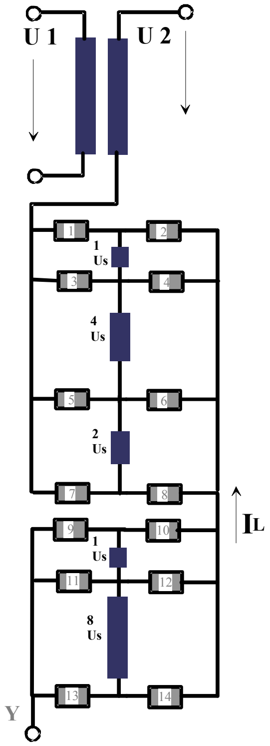
Figure III.11 Tap changer arrangement with four switched windings



14 pairs of thyristors

Thy 9, 10, 13, 14	block	12 Us
Thy 11, 12	"	8 Us
Thy 1, 2, 7, 8	"	4 Us
Thy 3, 4	"	3 Us
Thy 5, 6	"	2 Us

Figure III.12 Tap changer arrangement with fewer thyristor valves and more switched windings



14 pairs of thyristors

Thy 9, 10, 13, 14	block	9 Us
Thy 11, 12	"	8 Us
Thy 1, 2, 7, 8	"	7 Us
Thy 3, 4	"	6 Us
Thy 5, 6	"	5 Us

Figure III.13 Tap changer arrangement with more uniform voltage stresses on the different valves

Still another technique that could be used to optimize thyristor valve ratings is to separate the choice of thyristor valve voltage rating from the step voltage by an intermediate circuit. This allows selecting switched winding voltages to give optimum thyristor valve ratings and then insert the sum of the thyristor switched winding voltages to the main circuit through a booster transformer connected in series with the main winding. The turns ratio of the booster transformer ensures that the voltages of the switched windings correspond to the required step voltages. Such an arrangement is shown in Figure III.14. Figure III.14 incorporates the circuit of Figure III.13. However, the technique could be applied to any of the other thyristor switched winding arrangements. This is also one way to achieve uniformity in the thyristor valve design. It also can be used to avoid series connection of the thyristors by choosing suitable voltages for the switched windings. This can lead to the use of standardized thyristor valve assembly for tap changers with attendant cost savings from standardization.

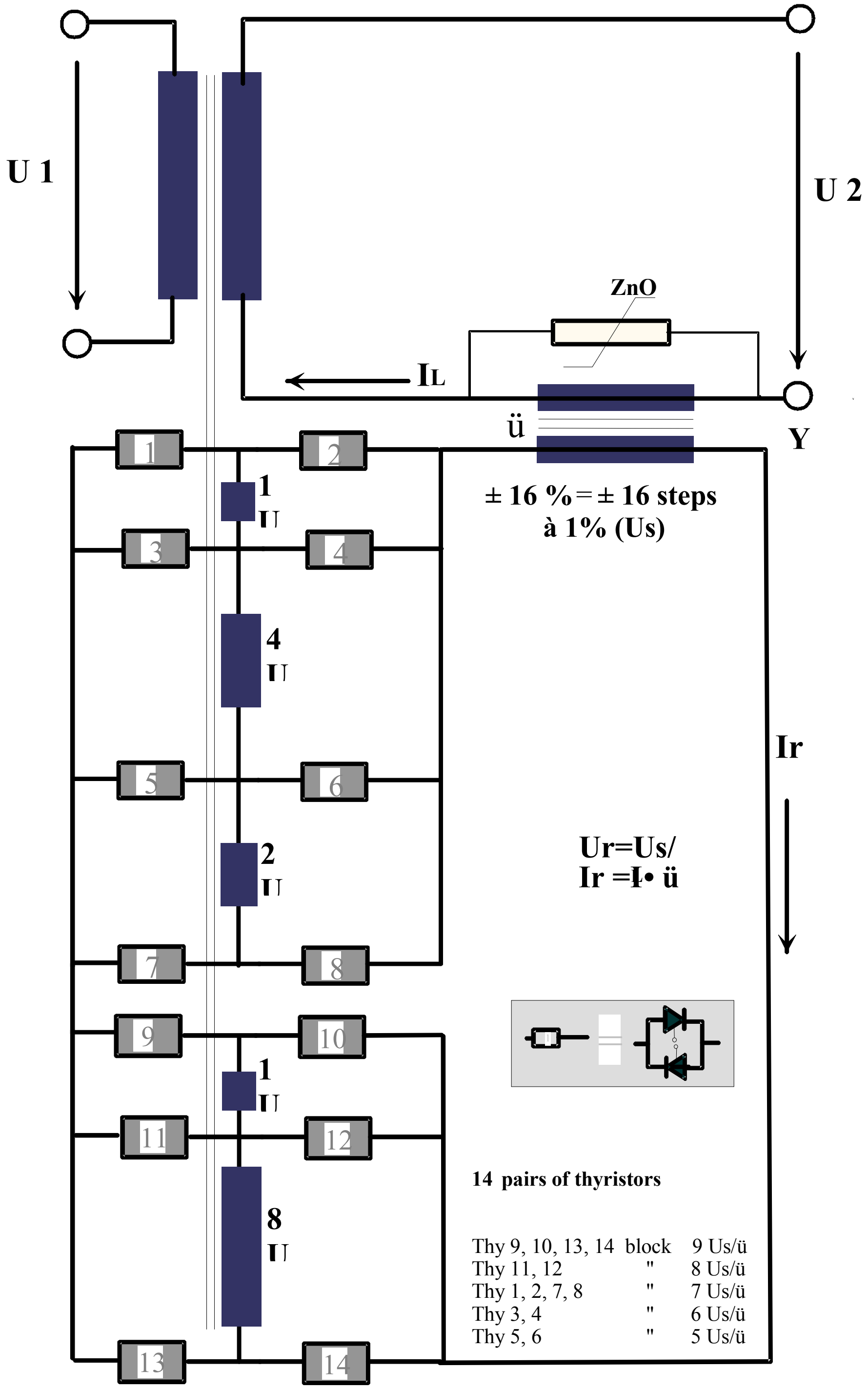


Figure III.14: Winding topology for regulation ± 16 % in an intermediate circuit with fully static thyristor OLTC

III.6 Conclusion

The system benefits of hybrid OLTCs with static switches in the diverter only - thyristor based or GTO based – compared to conventional OLTCs, especially those with vacuum switches, are marginal. However, substantial improvement in the speed and frequency of operation of a fully static OLTC could extend the use of OLTCs to enhance system performance in the areas of power system stability and sub-synchronous resonance.. It is quite feasible to get fully static OLTCs thyristor switched tap changer windings. They are not suitable for application to transformers designed for conventional OLTCs. Modifying the transformer design to accommodate the static OLTC is not a major technical challenge. The Working Group does not have data on the cost of such OLTCs.

There have been some attempts in the past to evaluate the comparative economics of static and conventional OLTCs [16]. However, they were based on assumptions regarding the maximum ratings of thyristors that are not valid today. The industry is encouraged to develop the necessary cost data based on presently available thyristor technology and the different circuit configurations presented in this report. That could then be compared with potential benefits, which are likely to be application specific.

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