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Matrix Switch Solid-State Load Tap Changers: A Design Study

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Technical Update, December 2009

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PRODUCT DESCRIPTION

Load tap changers (LTC) are among substation components that feature relatively high failure rates compared to other components. Successful development of a commercial solid-state load tap changer can potentially eliminate these failure rates. Although the academic literature is rich with several approaches to realize solid-state tap changers, successful solid-state devices have not become competitive with the state of the art. The project documented in this technical update explores a novel matrix switch interconnection approach to realizing solid-state load tap changers.

Results & Findings

The design study has found that the candidate solid-state LTC approach can perform competitively with resistive load tap changers in realizing well-regulated tap current levels during tap transitions.

Challenges & Objective(s)

Although realization of solid-state approaches to LTC can be readily made using various alternative approaches, making them comparable in performance with state-of-the-art approaches is a challenge. This is primarily due to the relatively narrow fault-handling capability of power semiconductors in solid-state circuits. The matrix switch interconnection approach studied in this project has potential for self-limiting the fault current and, therefore, provide a viable approach to realize a commercial solid-state LTC.

Applications, Values & Use

Continuing development of solid-state switching devices built using such materials as silicon, silicon carbide, and gallium nitride are enabling realization of more robust power electronics applications with higher performance and lifetime levels in comparison to state-of-the-art switching devices. This trend is expected to continue and eventually tip the scale in making them preferred alternatives to mechanical switching devices.

EPRI Perspective

EPRI is well placed to develop the advanced concepts that are being studied in this project by bringing together diverse constituents including academic researchers working with electric utility experts and equipment vendors who will commercialize the technology as results evolve to meet market place demands.

Approach

The objective of this project was to study the technical viability of the proposed matrix switch interconnection device in realizing load tap changers. A candidate commercial resistive-type LTC device was chosen to provide candidate specifications, and computer simulations have been used to demonstrate the technical performance of the proposed approach. Further activities are continuing to update the design to ensure proper operation and protection during fault conditions.

Keywords
Load tap changers
Transformers
Substations
Voltage regulation
Thyristors
Power electronics

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1 INTRODUCTION

Background

Legacy Load Tap Changers (LTC) on utility transformers are used widely in substations for voltage regulation. Photographs of example tap-changers are shown in Figure 1-1. They are based on electro-mechanical technology and include numerous precision mechanical parts, which wear and require frequent maintenance and down time. Photographs shown in Figure 1-2 illustrate the complexity of the construction and the number of parts in a typical load-tap changer. The legacy tap changers also create arc when switching taps, causing degradation of the cooling liquid and deteriorating the dielectric property. Figure 1-3 shows the degradation of electric contacts due to aging and/or overloading. Figure 1-4 shows the distribution of failure of transformer components from a study, highlighting the dominance of LTC being the single most important maintenance problem with substation transformers.

Some of the recent work has reassessed the feasibility of reliable, compact, and cost-effective solid state load tap changers, followed by a concept demonstration of power circuit topology. On the other hand, in spite of these efforts, successful development of a reliable commercial device has remained elusive. A previous EPRI study (Project 41C3084/6658-6424 from the year 2000) titled ‘Evaluate Solid State LTC Options for Medium Power Transformers’, found numerous ideas for thyristor-based LTC in the literature and in U.S. patents, while identifying a few of that had very limited commercial applicability for medium-power transformer voltage regulation. The majority of the conclusions were drawn from the application of thyristor-assisted (hybrid) LTC and completely thyristorized solid-state LTC.

While thyristor based power electronics devices have a relatively long history of application in utility electrical systems, the application of advanced semiconductor device technology such as IGBTs and IGCTs have not been definitively explored in LTC applications. Continuing developments in such advanced power electronic switching devices are enabling enormous efficiency improvements in the electrical energy utilization sector. Multi-megawatt solid-state power control systems are becoming increasing applied in critical industrial electrical installations. Industrial demands for improved performance and energy productivity, coupled with customized high volume production, favorable scales of economy and increasing technical maturity of power converters are resulting in reduced costs approaching a few cents per watt in selected applications.

From this perspective, this project takes a fresh view at the development of solid state LTC using actively commutated semiconductors such as IGBTs and IGCTs with a goal to realize a compact, reliable, and cost-effective solution. On the basis of the power circuit operation, additional maintenance and supervisory functions can be added to further improve the performance, life cycle, and operating cost of the power delivery system.

Figure 1-1
Photograph of Load Tap Changers [From ABB On-load tap-changers, type UC and VUC; and On-load tap-changers, type UBB, Technical Guides]

Technical Approach

This project is aimed at taking an alternative approach of develop a load tap changer with solid-state devices, with a goal to eliminate the moving parts and the electrical contacts. The approach utilizes a multilevel matrix interconnection of semiconductor switches described further in this update using H-Bridge building blocks. The use of multilevel semiconductor interconnection has been used with excellent performance levels in commercial motor drives at multi MW levels while maintaining reliability. The approach is systematic, with a set of semiconductors rated to the maximum voltage of each tap and 1 per unit load current. Thus the semiconductors are rated only at a fraction of the transformer rating. The gating pattern of the bridges determines the tap setting.

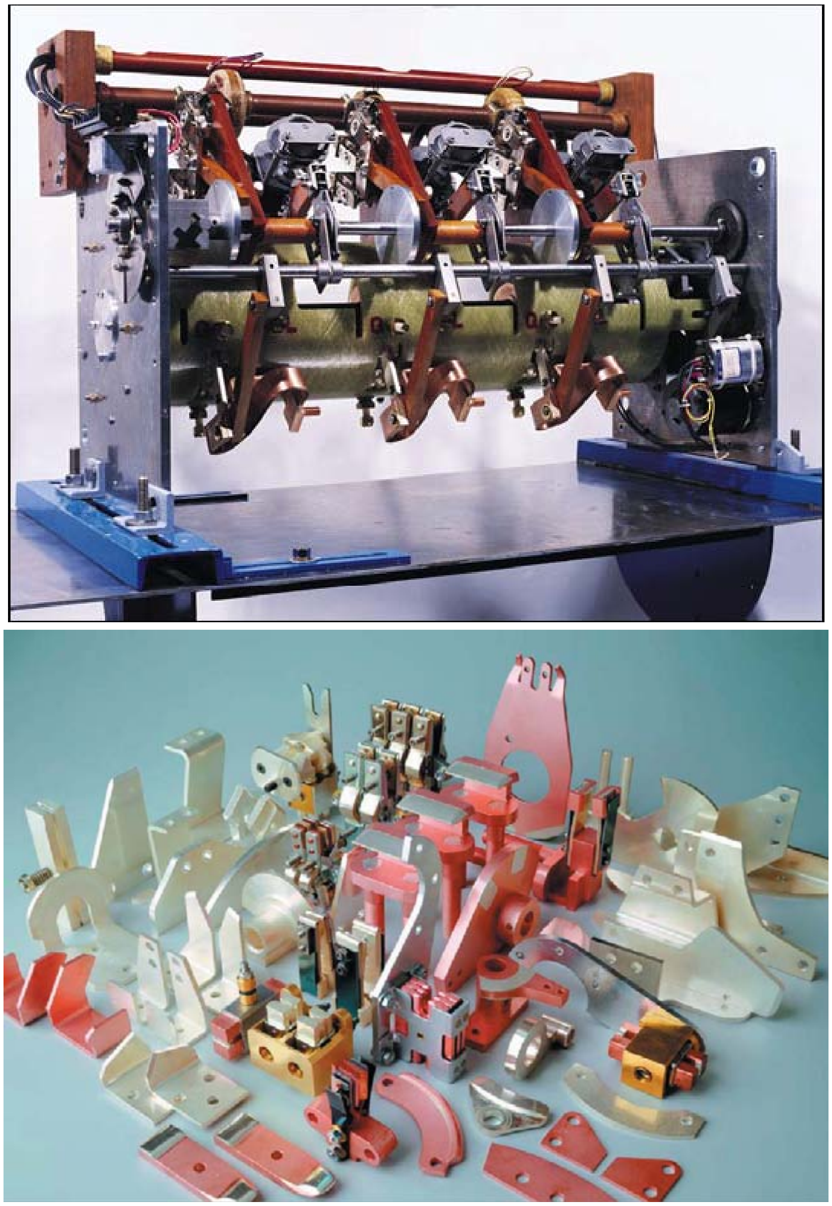

Figure 1-2
Illustration of Complexity of Construction and Parts in Load Tap Changers. [From Waukesha Electric Systems, Load tap changer expertise, and HIGH VOLTAGE SUPPLY™, Load tap changer components]

Objectives

The objective of the proposed project is to conduct a design study for a load tap changer using commercial state-of-the art semiconductor devices connected in a Matrix interconnection with performance and reliability levels comparable to commercial state-of-the-art load tap changers.

Figure 1-3
Photograph of Degraded Electrical Contacts from a Load Tap Changer [From Waukesha Electric Systems, HIGH VOLTAGE SUPPLY™, Load tap changer components]

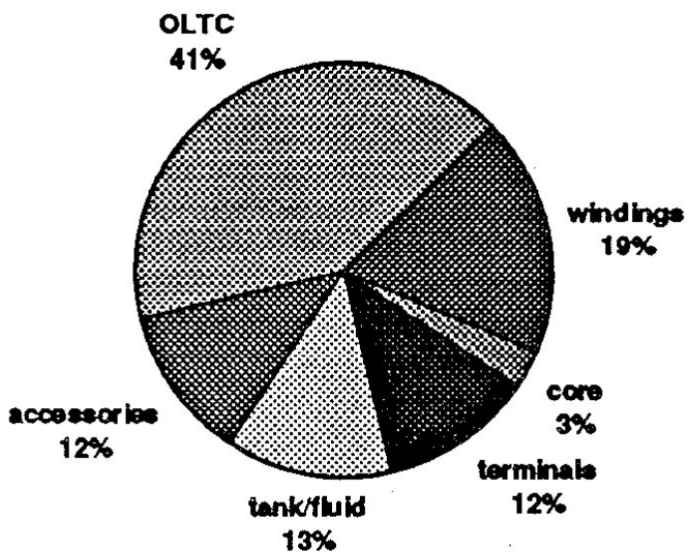

Figure 1-4
Typical Failure Distribution for Substation Transformers with OLTCs (From Bengsston, IEEE Transactions on Power Delivery, July, 1996)

In the project activities, specifications of commercial state-of-the art load tap changers have been reviewed, and a candidate system application for appropriate matrix interconnection of semiconductor switches has been developed. Performance levels of using the proposed matrix switch interconnection has been analyzed and compared with the commercial state-of-the-art mechanical tap changer. Detailed computer simulations have been performed to verify the performance of the candidate design under normal operating conditions.

The concept and operation of matrix switch interconnection of semiconductor switches is presented in Chapter 2, followed by a review of the candidate commercial state-of-the-art load tap changer design that uses a resistive insertion device during operation in Chapter 3. In Chapter 4 computer simulation results illustrating the operation of the matrix switch interconnection compared against the operation of the resistive device is presented. Continuing activities of the project are presented in Chapter 5, followed by a concluding discussion in Chapter 6.

2
MATRIX SWITCH POWER CIRCUIT TOPOLOGY

Background

Realization of solid state LTC devices using advanced power electronic devices such as IGBTs and IGCTs are based on the application of switching power converter topologies.

Switching power converter topologies consist of various switch throws configured in specific patterns between power sources and loads along with appropriate reactive elements external to the switch throws. In most instances, canonical switching power converters consist of single pole multiple throw switches, wherein inductors appear in series with poles and capacitors appear in parallel with throws. Controlled operations of the throws regulate the instantaneous energy transfer among the sources, loads and reactive elements. By regulating the interval of times during which specific energy transfer among the elements occur, and through repetitive operation of the switches, average power flow between sources and loads are modulated. The presence of reactive elements ensures continuity of power flow at the load and source terminals to maintain adequate levels of waveform quality. However, the net energy transfer across the reactive elements is zero when averaged over a switching period. The throws of the switches themselves are incapable of storing energy and are realized using a combination of semiconductor switches consisting of unidirectional voltage blocking and current conducting capabilities configured appropriately to fit the application requirements. Switching converters based on these principles allow the realizing of dc-dc, ac-dc, dc-ac and ac-ac power conversion functions.

Among the switching power converters, multilevel matrix switch power converters are among the family of power converter topologies for realizing higher power levels. They have emerged to become the choice topology for reaching multi-MW power levels. Two major motivating factors may be identified to be the driving force behind this trend: (a) they allow the use of power semiconductor switches rated at lower voltage to realize higher voltage systems, which are preferable at higher power levels to limit the current density in conductor systems to reasonable levels; (b) it is easier to synthesize high quality waveforms in the power conversion process without the use of expensive reactive elements to filter the switching harmonics, particularly when the switching frequency is limited at high power levels. Given these motivating factors, there are two major classes of multilevel converters, namely stacked ac bus power converters and stacked dc bus power converters from the point of view of the location of the series connection to realize the high voltage system. Among the stacked dc bus converters, extending the number of levels beyond three has not become commercially viable due to the complexity of the power circuit layout and packaging. On the other hand, stacked ac bus power converters have been realized with relatively large numbers of levels in commercial systems, arguably due to their modularity of the power circuit package. However, maintaining the various degrees of galvanic isolation to allow series connection of the ac outputs from individual power converters requires the use of transformers that typically use low frequency magnetics, thereby adding to the cost of the system. Thus, from a practical sense, the total number of levels used per phase has been limited to a handful.

Ideally, if the topological structure of the multilevel converter allows it to be scaled to a countless number of levels, their applicability may be extended beyond the power levels that are practically limited by voltage and current ratings of available of commercial power semiconductor devices at reasonable cost. Moreover, such a topological structure will also allow the realization of power converters of lower power levels using power semiconductors that are rated at much lower voltage and/or current ratings, thereby leading to economies of scale that are much more favorable.

More recently, the concept of incorporating a bridge arrangement of switches with a nominal amount of energy storage as the control element in realizing various switching power converters has been introduced. Topologies of power converters that use such bridges have been presented and demonstrated in recent years as three phase ac to three phase ac matrix converters and as single phase ac to three phase ac dual bridge converters. They have been introduced with specificity and in isolation their fundamental properties have not been illustrated and exploited. Furthermore, many of the control techniques that have been presented are based on heuristic approaches and the particular relationship of the operational principle and structure of the power converter with existing canonical power conversion approaches are unclear. The objective of this chapter is to present a systematic study of the topology geared towards application to a solid state LTC. This builds upon the study of the primitive capacitive storage embedded bridge (CSEB) that is introduced as a building block that may be used to realize solid state LTC. A behavioral model of the CSEB is developed to model its power and energy transfer properties. Specific operating modes of the CSEB are identified along with their semiconductor realizations, including the operation of a string of series connected CSEB. Based on the behavioral model of the configuration, operating constraints of the topology are identified for the chosen application.

Capacitive Storage Embedded Bridge

A simplified schematic diagram of the CSEB in full bridge configuration is shown in Figure 2-1. Bulk energy storage (CS) in the capacitor is typically in the form of dc, thereby providing an appropriate bias voltage or current for the switching devices that constitute the bridge circuit. The presence of LB indicates stiffness of the bridge terminal current, which may be provided by an incidental amount of inductance in series with the bridge, with minimal amount of energy storage in it.

The realization of the throws of the CSEB depends on the polarity of terminal currents and the polarity of the bias voltage. Assumption of unipolar bias voltage v_S and bi-directional terminal current i_B leads to a classical H-bridge consisting of gate-turn-off semiconductors such as IGBTs, IGCTs with antiparallel diodes. In case of bi-directional bias voltage and bi-directional terminal currents, a pair of anitparallel thyristor devices may be used in conduction with integral cycle of phase controlled switching. The full bridge topology enables bipolar values for v_B and i_B through appropriate control of switch states, as would be required for a solid state LTC application.

Furthermore, an arbitrary number (n) of CSEBs either in the symmetrical full bridge or the asymmetrical half bridge configuration may be connected in a series string. Typically, these bridges would consist of identical modules for the sake of simplicity and convenience in packaging, design, n+1 redundancy, control and realization. Since they are connected in a series string, they carry the same current and under most circumstances, their dc bias voltage level will nominally be identical if their respective bridge operating conditions are also identical.

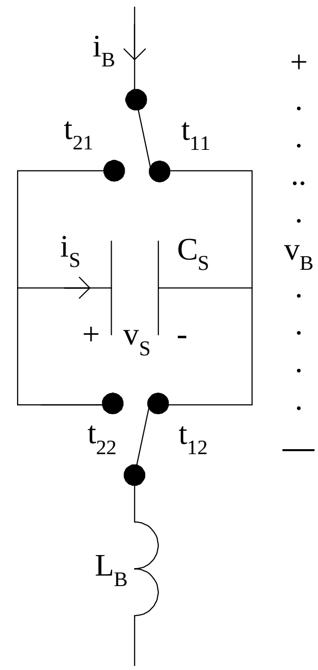

Figure 2-1
Schematic of CSEB in full bridge configuration alongside a single throw switch

CSEB Strings in a Solid State LTC

Figure 2-2 illustrates the power circuit schematic of the application of a three-tap Solid State LTC using three strings of CSEBs realized using IGBTs with antiparallel diodes for switch throws. In this case, nominal voltage rating of power devices in each of the bridges will be about one-third the voltage across the taps. Furthermore, in order to provide n-1 redundancy to accommodate safe operation during possible failures, the devices may be rated at one half the voltage across the taps. Although IGBTs are illustrated in the figure, they may be substituted for other gate-turn-off devices such as IGCTs, silicon carbide mosfets, super GTOs etc. The application of thyristor devices such as Silicon Controlled Rectifiers or SCRs are also feasible in various semi-controlled and fully controlled configurations with restrictions on switching operations limited to natural commutation.

The number of series connected strings is an arbitrary design variable that can be appropriately selected to meet the voltage requirements of the taps for application of the LTC and the availability of power semiconductor devices with appropriate ratings. In recent years, gate-turn-off power devices rated at several kV voltages and several kA currents are becoming commercially available in robust grades for snubber less switching operations.

The use of CSEBs provide a means for applying these devices in the LTC in a manner that improves the reliability of the overall system as opposed to be seen as liability as has been the case with the circuit configurations studied for solid state LTC realizations in the past.

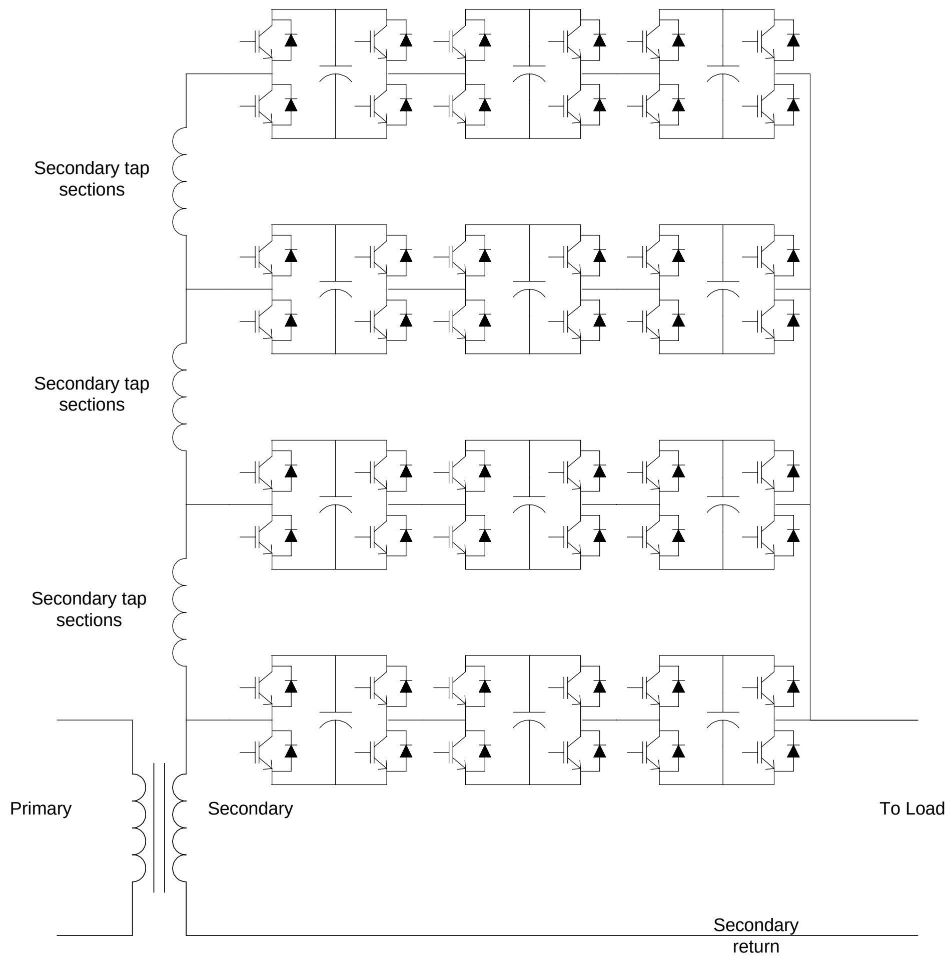

Figure 2-2
Power circuit schematic diagram of a three-string CSEB in a Solid State LTC with three taps realized using IGBTs

Summary

This chapter has provided as brief overview of the operation of a CSEB as a building block that can be applied in series string for various power control applications. This configuration is being developed further for large scale power electronics applications be selected manufacturers for applications in electric locomotive traction and power transmission applications. A primitive approach for their application for realizing a solid state LTC has been presented further in the chapter. The operation of the proposed devices is studied using computer simulation model as described further in the chapter 4.

3
STATE OF THE ART APPLICATION REVIEW

In this chapter, the classical LTC approaches are briefly presented, and a commercially-available candidate is selected, to be studied and compared to a solid-state counterpart. The solid-state LTC is aimed to perform as good as or better than the classical LTC, and to provide a solution with no mechanical moving parts.

Classical Load Tap Changers

Load tap changers are an important component of modern substations, mainly on the distribution level. Their job is to commutate among available transformer taps to perform voltage and/or phase regulation, being this action carried out on the high- or low-voltage side. LTCs have been present for a long time (see Appendix C on [1] for some examples), and their basic switching principle has remained almost intact over the years. Since the commutation between adjacent taps cannot be instantaneous in practice, different approaches has been used to mitigate the effects of a possible loss of load (open-circuit condition) or winding over-current (short-circuit condition). Those mechanisms are presented below.

Oil-type LTC

Since the system unavoidably opens a circuit on the transition operation, arcing could occur on the LTC terminals. To mitigate this problem, the LTC can be immersed in oil and realize all the operation under oil. Transformer oil is often used on this approach.

The switching is generally performed using one of the following principles:

1. Diverter switch: Used in conjunction with a tap selector, it allows the commutation between two adjacent taps. As shown in Figure 3-1, the diverter switch moves from one tap to another passing by two transition elements that limit the circulating current. The tap selector moves to the desired tap in advance.

2. Selector switch: It joins the diverter switch and tap selector in one unit. In Figure 3-2 an example of selection switch is presented. Two commutating sequences are usually applied on the selector switch: (i) the flag cycle, where the current is diverted from the main contacts before the circulating current starts to flow, and (ii) the symmetrical pennant cycle, where the circulating current starts to flow before the through current is diverted from the main contacts [2].

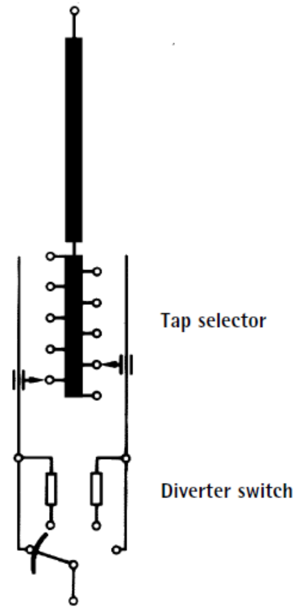

Figure 3-1
Ilustration of the diverter switch principle [From Maschinenfabrik Reinhausen: Technical Data – General Section. Technical Data TD 61]

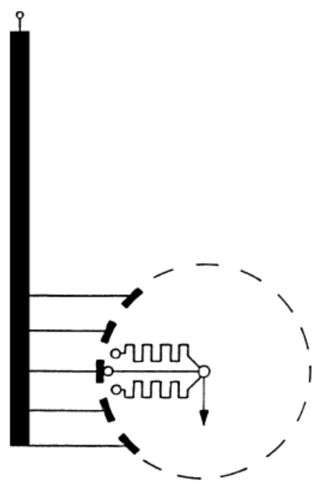

Figure 3-2
Ilustration of the selector switch principle [From Maschinenfabrik Reinhausen: Technical Data – General Section. Technical Data TD 61]

The transition element defines the following categories of load tap changers:

1. Resistor-type LTC: Uses wound resistors as transition elements.

2. Reactor-type LTC: Uses coupled inductors as transition elements. This arrangement is usually called preventive autotransformer.

Vacuum-type LTC

Instead of using the oil medium for the arc quenching, vacuum can also be used. Vacuum interrupters have been developed and successfully applied to load tap changers on the last decades. There still exist transition elements and switches, but they operate under no stress condition, and the vacuum interrupters extinguish the arc. The transition elements remain the same, and the switching principle is slightly changed, but otherwise equal.

More details on vacuum-type LTC can be found on Chapter 13 of reference [3].

LTC Candidate

The candidate was selected using the following criteria:

- The selected LTC has to be rated for relatively low power and low voltage, since the candidate might be tested in the future on a university laboratory, where facilities typically don't include access to high voltage levels. However, the candidate must preserve all the essential characteristics and be representative of its family of devices.
- The candidate should be readily available on the market, and manufactured by several different companies if possible. This ensures a further comparison with a well known, accepted LTC solution.
- The selected model should be able to be easily retrofitted with a power electronics solution.

From the LTCs available in the market, oil-type LTC technology is chosen, since it is massively applied worldwide by several manufacturers. From the different enclosures, in-tank models (Figure 1-1) are difficult to retrofit because they have an odd shape optimized for diverter switches and internal transformer connections. Out-of-tank models are preferred in this case (Figure 3-3) due to its external location with respect to the transformer housing, and its simple design.

Manufacturer of out-of-tank LTCs include ABB (UZ series), Maschinenfabrik Reinhausen (RMV series), and Shanghai Huaming Power Equipment (HWV series). From those manufacturers, ABB provides the most comprehensive documentation, including selection guides, installation and commissioning guides, and order forms. Therefore, an ABB LTC will be used as the candidate.

Table 3-1 lists the specifications of the candidate LTC. Note that the specifications consider a three-phase LTC. However, only one phase will be studied and simulated in the following pages of this report. The manufacturer gives the option of designating a LTC to be single-phase. For that case, the designation changes to UZ ELE 200/150, and the power rating is reduced to 33.3 kVA. The rest of the fields remain the same.

More details of the ABB UZ type LTC can be found on [4],[5],[6].

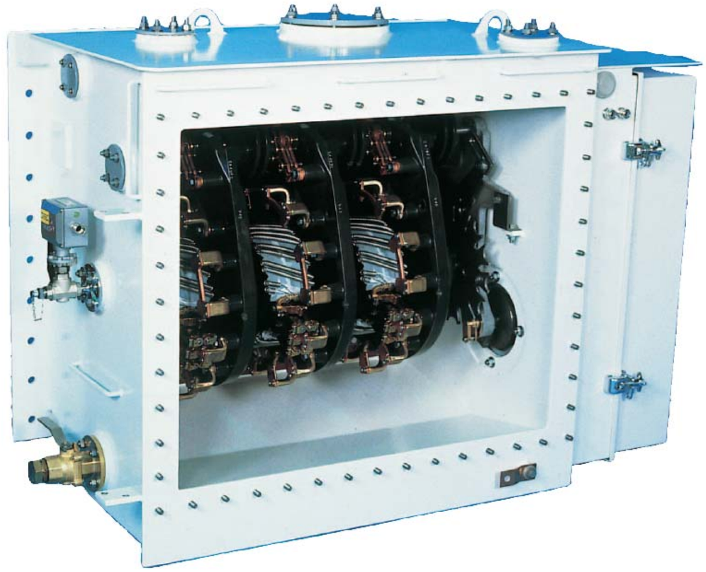

Figure 3-3
Ilustration of a on-tank load tap changer [From ABB: On-load tap-changers, types UZE and UZF with motor-drive mechanism, type BUF 3, Installation and commissioning guide, 1ZSE 5492-115]

Table 3-1
Detailed specification for the candidate LTC

Data	Value	ABB Field code
Manufacturer	ABB	
Designation	UZ ELN 200/150 (*)	BA
Type	UZE or UZF, network type	AA
Type of switching	Linear	AG
Type of connection	Three phase (*), wye-wye connection	AC
Impulse withstand	200 kV	AE
Maximum rated through-current	150 A	BE
Rated power	1 MVA	AB
System voltage (transformer ratings)	3.85 kV / 480 V, 60Hz	AC, AE
Regulating range	-5% -- 5%, 2.5% step voltage on HV side	AC
Regulating steps	5	BC
Rated step voltage	96.25 V	BD
Effective number of turns (tap labels)	1..5	BH
LTC placement	On the line end of HV side	AD

4

DESIGN SIMULATION STUDIES

For the purpose of this study, a simplified model of a LTC is considered. This model preserves the main characteristics of a full LTC. In particular, some of the mechanical operation details may be lost. However, due to the solid-state nature of the matrix switch LTC, mechanical operation details are not of interest for the comparison.

The main simplifications of the current model are:

- Only two taps are considered on the primary side. Voltage step between taps is 2.5%.
- The system is fed from a resistive line and ideal source. The use of a resistive line imitates the behavior of a low-voltage (distribution-level) line. This selection was made to further enable the comparison of these results with future laboratory prototype testing.
- Only a single phase is simulated.
- Resistive load is considered for the comparison. On preliminary investigations, the differences in the response of the system under an R-L load are negligible.

Operation of Baseline System

The baseline case-study system operates under no current limiting scheme. Its purpose is to estimate the amount of over-current that flows through the transformer windings when the taps are short-circuited for a small time. This system is shown in Figure 4-1.

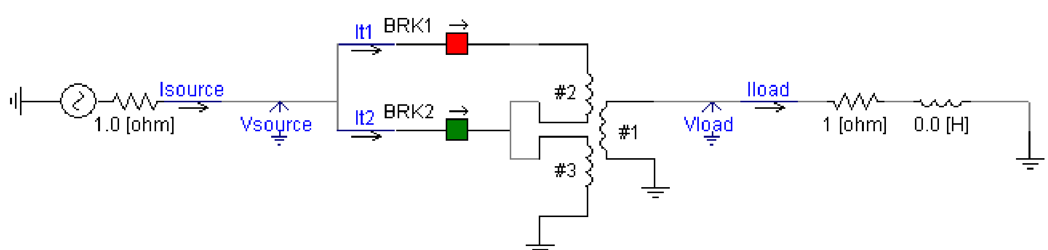

Figure 4-1
Illustration of PSCAD Schematic of the Baseline Case-study System without the Use of LTC

This system contains only two ideal circuit breakers that operate on a synchronized scheme:

a) The simulation starts with the system feeding the lower tap (winding #3 on the figure).

b) After the steady state condition is reached, the breakers are operated for two electrical cycles, keeping both taps short-circuited during the transition (i.e. shorting winding #2).

c) Finally, the system is left operating at the upper tap (windings #2 and #3 in series) for the rest of the simulation.

This sequence is shown in Figure 4-2, where circuit breakers boxes are solid (black) for closed position, and clear (white) for open position.

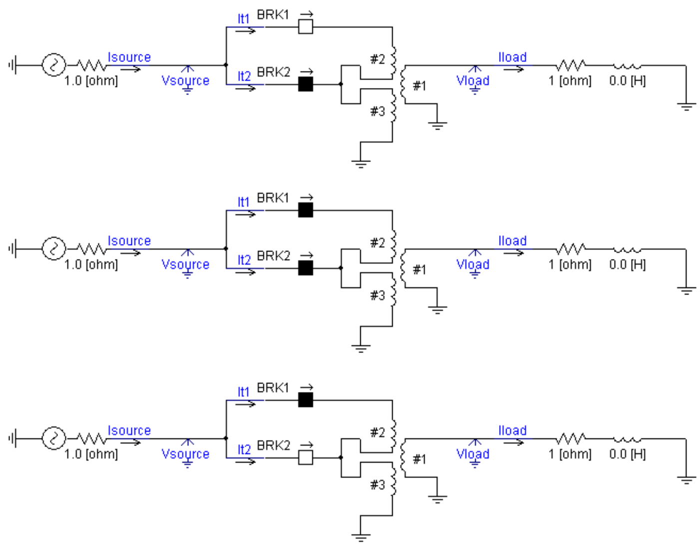

Figure 4-2
Illustration of Sequence of operation of the Switches in the Baseline Case-study System without the Use of LTC

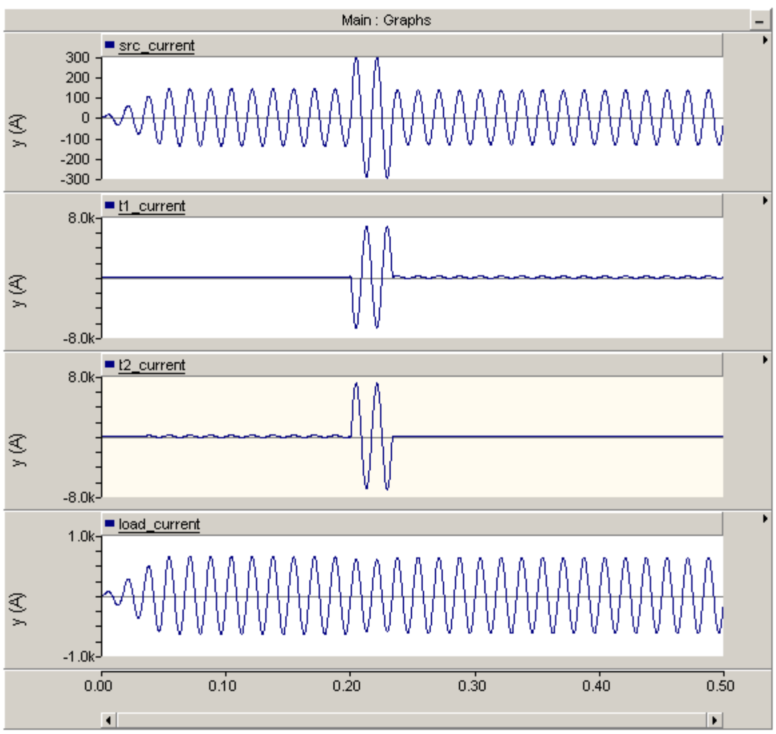

Figure 4-3
Computer simulation results illustrating the operation of the Baseline Case-study System without the Use of LTC

The simulation results of Figure 4-3 show that the current on the transformer windings (second and third curves) reach an extremely high value (6.6kA peak, 77 pu). However, the line (or source) current is only doubled.

Operation with Resistive LTC

The resistive LTC comprises two resistive elements that mechanically provide transition impedances for the operation of the transformer. On Figure 4-4, a model for the resistive LTC is shown. It considers the same source and load setup of the baseline case-study system, and adds two circuit breakers tied in series with the transition resistors.

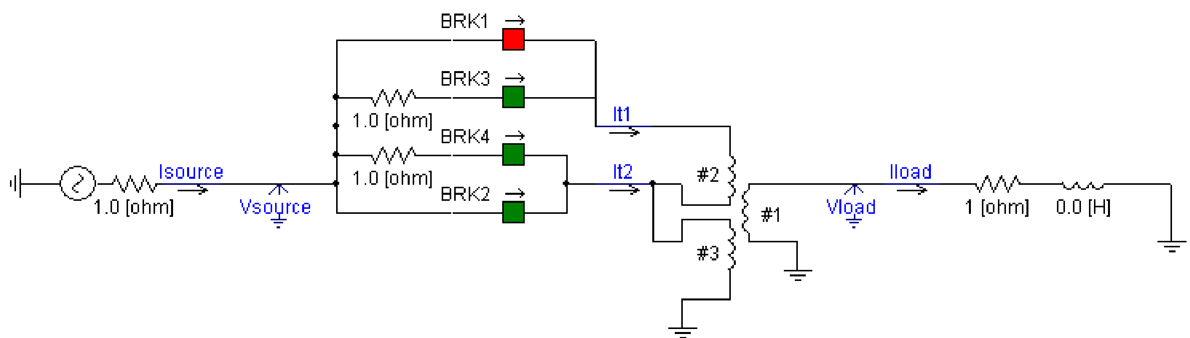

Figure 4-4
Illustration of PSCAD Schematic of the Case-study System Using Resistive LTC

The value of the transition resistor is usually selected in terms of the rated step voltage and through current of the taps. Using the step voltage and rated current as basis, the transition resistor usually has a value of 1 pu. For the purpose of the simulations, 1 ohm is chosen to be representative (otherwise bigger) value of transition resistor.

The sequence of operation for the resistive LTC (flag cycle) is shown in Figure 4-5:

a) As in the previous case, the simulation starts with the system feeding the lower tap. After the steady state condition is reached, the breakers are operated for two electrical cycles.

b) On the first half cycle, the load current is diverted through the lower transition resistor.

c) On the next two half cycles, both transition resistors operate together.

d) On the last half cycle, the higher transition resistor operates alone.

e) Finally, the system is left operating at the upper tap.

Simulation results of this operating sequence are shown in Figure 4-6. The resistive LTC effectively limits the winding current during the transition. Current levels are lowered, and the load is shared by both taps. Moreover, there is no noticeable perturbation on the load side.

Note that in a real resistive LTC, the transition usually takes 50ms (3 cycles). However, the transition is asynchronous: the selector switch might see arcs on the contacts until the current crosses zero. Then, the simulation is simplified and the transition in only carried out in two cycles at perfect zero crossing. This way, the simulation is a best-case example of resistive LTC

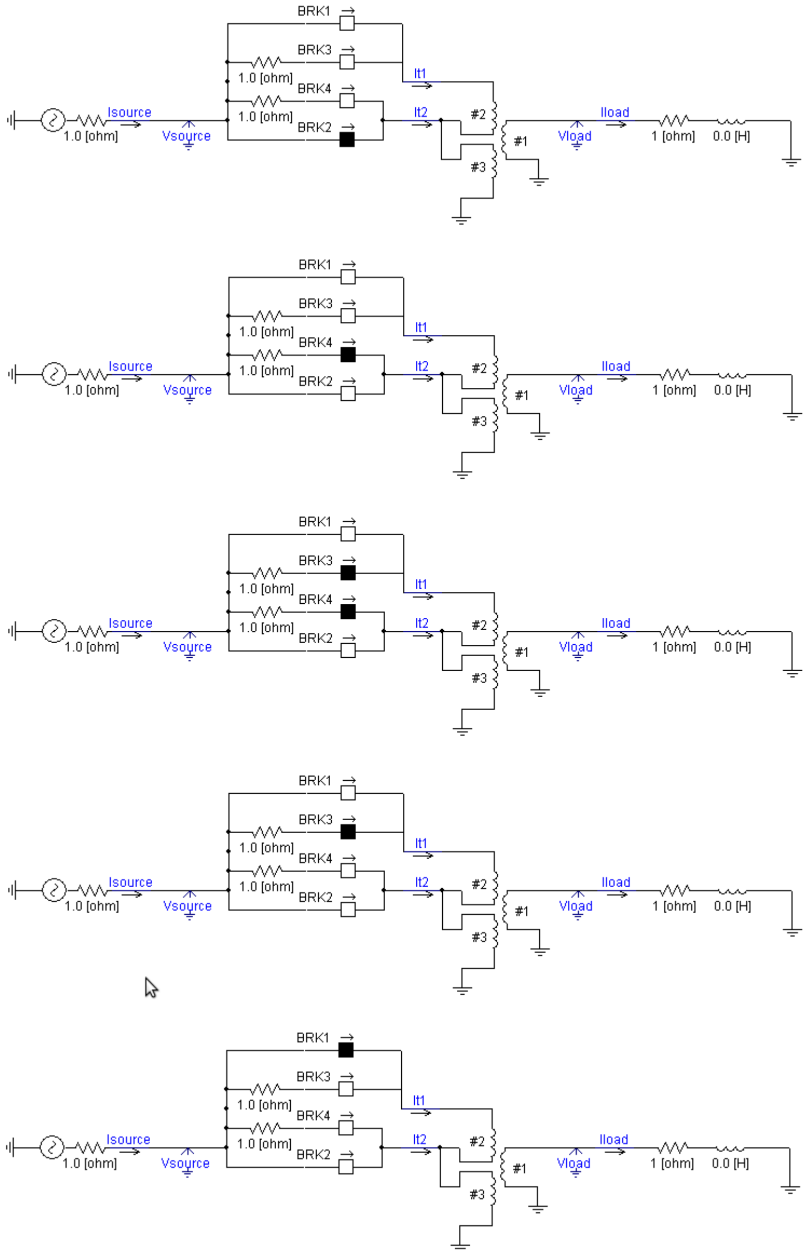

Figure 4-5
Illustration of Sequence of operation of the Switches in the Baseline Case-study System Using Resistive LTC

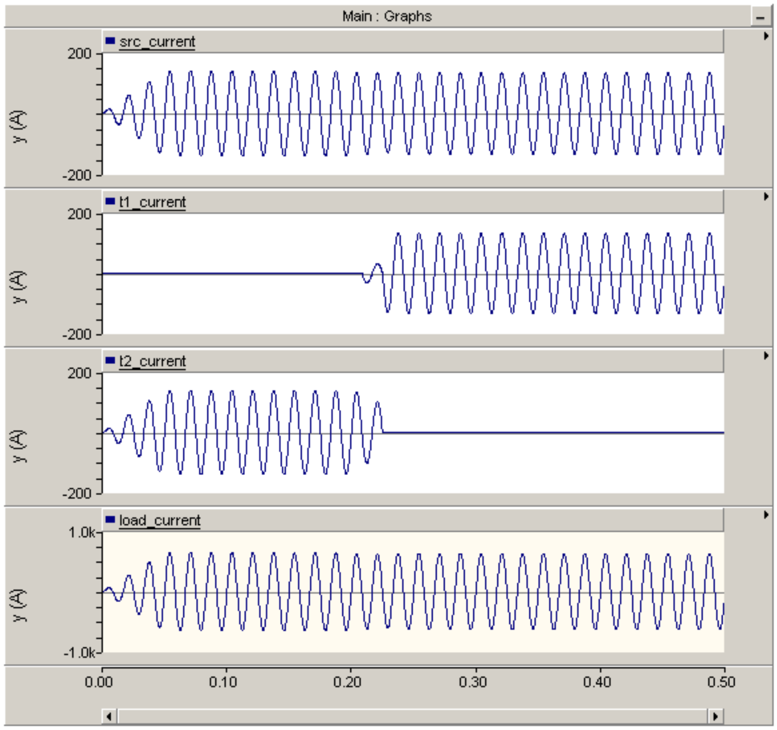

Figure 4-6
Computer simulation results illustrating the operation of the Baseline Case-study System Using Resistive LTC

Operation with Matrix Switch LTC

The matrix switch LTC system includes in general one string of CSEB per tap, forming a BoB network. However, the presented model of Figure 4-7 is simplified to one CSEB per tap. The system configuration is the same as the previous cases, except for the BoB stage.

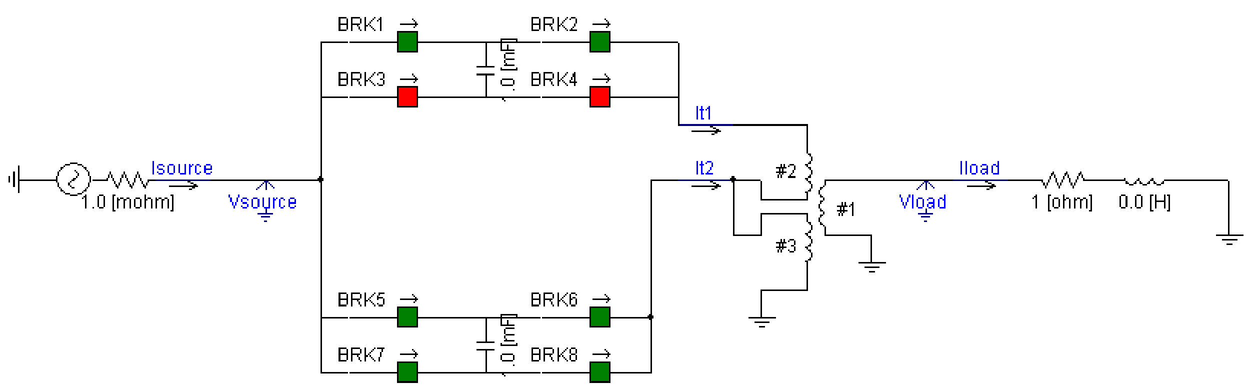

Figure 4-7
Illustration of PSCAD Schematic of the Baseline Case-study System Using the Matrix Switch LTC

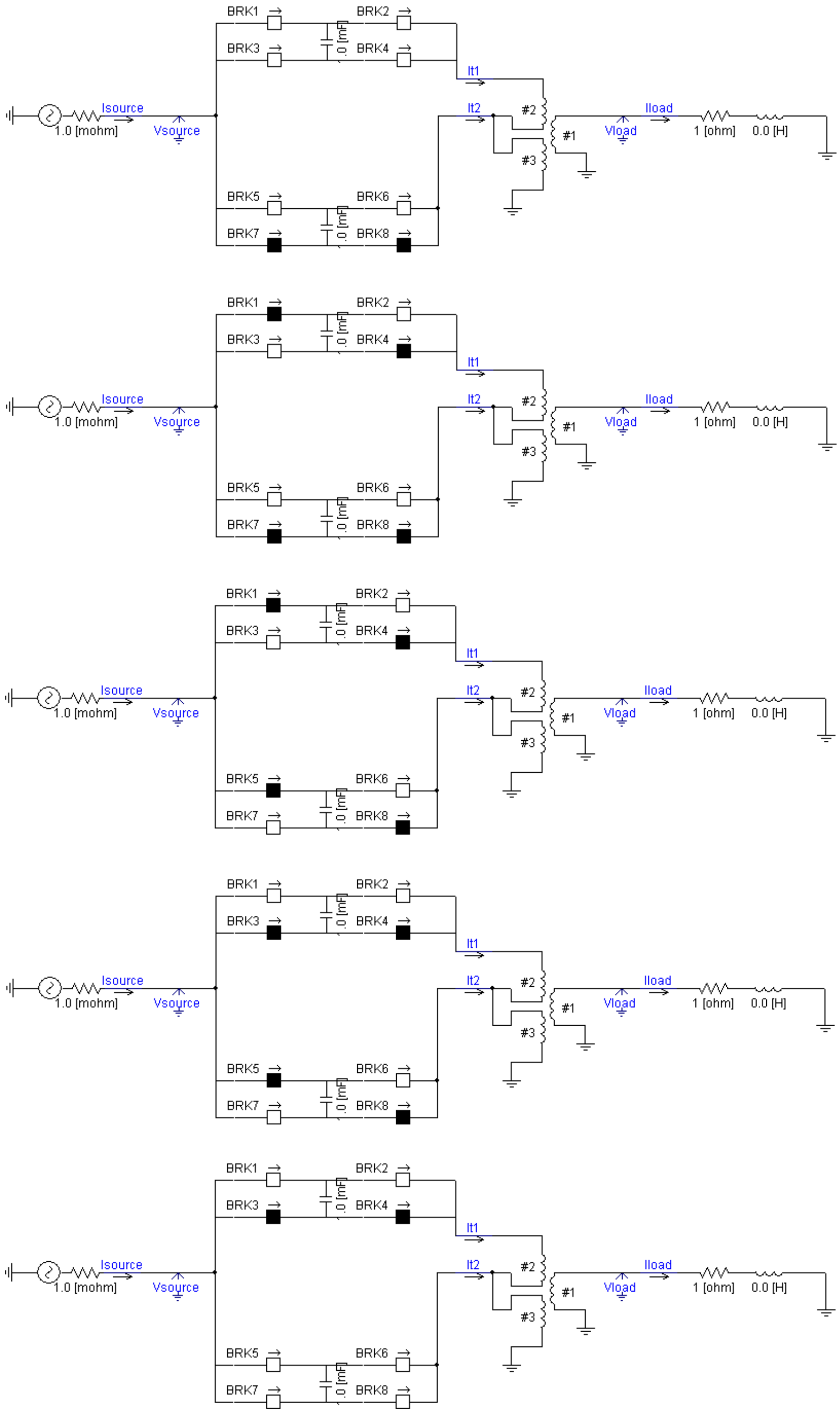

Figure 4-8
Illustration of Sequence of operation of the Switches in the Baseline Case-study System Using the Matrix Switch LTC

The sequence of operation for the matrix switch LTC is shown in Figure 4-8:

a) The system starts feeding the lower tap. The lower bridge acts as a short circuit, and its capacitor doesn't play role so far.

b) The transition begins when the upper bridge is enabled, placing the capacitor in the path of the upper tap. The upper bridge then provides a controlled current path for the upper tap current.

c) After one cycle, the lower bridge is also operated to put its capacitor in the current path. At this point in time, both bridges share the load current.

d) After a whole cycle, the lower bridge is disabled, and only the upper bridge is left enabled.

e) Finally, the upper bridge is put in short-circuit state, and the transition in complete.

Simulation results of Figure 4-9 show a successful limitation of the transition current. The behavior is similar to the resistive LTC case. The perturbation on the load is unnoticeable.

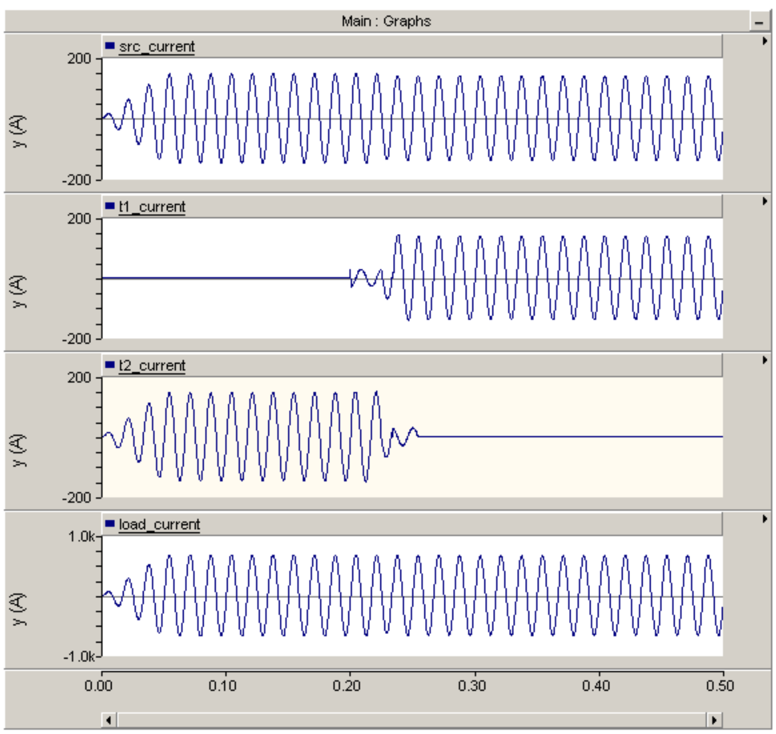

Figure 4-9
Computer simulation results illustrating the operation of the Baseline Case-study System Using the Matrix Switch LTC

Summary

For the baseline system presented in this section, two simplified LTC approaches were simulated. The classical approach is the resistive LTC system, while the novel approach is the matrix switch LTC system. Both systems presented similar response under operation, performing an effective limitation of the winding currents during the transition.

Similarities:

- Both systems go through the same number of steps to perform the tap change.
- Both LTC approaches take similar amount of time to finish the transition.

Differences:

- Matrix switch LTC system has no mechanical moving parts.
- While the transition time seems to be larger in the case of matrix switch LTC, the operation time on a classical LTC is in practice nondeterministic, and depends on the transformer loading, insulating medium (oil) quality, etc. In contrast, the matrix switch LTC can be controlled continuously on over the transition period. For the purposes of this report, CSEB operations are carried out when the current crosses zero. This could be changed with the introduction of modulation on the switches (not simulated so far).
- Resistive LTC has greater power losses compared to the matrix switch LTC. This can be justified since the LTC tap currents circulate on the LTC resistor elements for a few cycles, while in the matrix switch LTC there are no resistive elements, but only switches and energy storage elements. Power losses have an impact on the lifetime and mean time between failure (MTBF) of mechanical and electrical components. The matrix switch LTC is then expected to be more reliable. For a discussion on the reliability issues, see Chapter 2 of [1].
- From the system's control point of view, the matrix switch LTC is more flexible. On a classical LTC, the transition time is only controlled by mechanical means. Typically, springs are pre-compressed and their energy is released to the switching mechanism during the operation. Hence, the operator doesn't have any control on the transition period. On the other hand, the matrix switch LTC has complete control over the switches before, during, and after the transition[1].

As a conclusion, the simulation results support the concept of a matrix switch LTC as an alternative to the classical LTC, and a valid retrofit candidate.

[1] Partial control might be achieved in case of asymmetrical half-bridge topology, or the use of ordinary thyristors (gate-turn-on only) devices.

5
CONTINUING ACTIVITIES

Operation during faults

As said in the previous chapter, one of the key characteristics of the matrix switch LTC is the controllability of the system at all time. This enables different control strategies to be applied on different situations.

One of the most challenging situations for a power electronics system is a fault condition. In general, fault conditions are manageable with well rated semiconductor devices and careful system designs. There are commercial power electronics products that have successfully survived fault conditions.

A novel control strategy might be applicable in the matrix switch LTC topology, and can be explained as follows. When a fault condition appears on the system, one end of the CSEB string will see a reduced voltage level. Let's consider that the voltage is near ground level on the load side. In this case, we will have an equivalent system with one end at ground, and the other end at the line voltage. Fault current would flow through the matrix switches if no action is performed. However, since the CSEB string is able to behave as an inverter (dc-ac converter), it's possible to synthesize an adequate AC waveform at the line end, such that the current through the switches is minimized.

This control idea is presented in Figure 5-1, where the upper part of the figure represents the behavior under normal operation, and the lower part represents the behavior under fault conditions. This would contribute to better dynamics on the grid nearby, in situations where the classical LTC cannot operate.

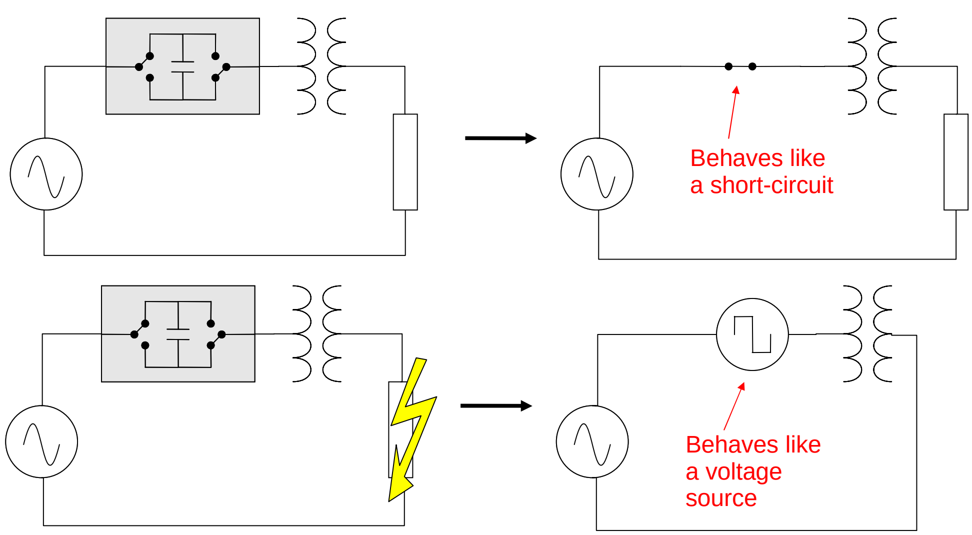

Figure 5-1
Control approach for fault conditions

Start-up and Bridge Energy Storage Balancing

As may be observed the power circuit interconnection of the matrix switch elements, the bridge capacitor plays an important role in absorbing and diverting the currents appropriately during tap changes. During this period, the energy balance in the bridge capacitor elements need to be maintained at a steady level. Furthermore, during start-up and fault transient conditions, it is necessary to ensure that the bias voltages in the bridge capacitors are maintained at appropriate levels. This may be readily accomplished by controlling the gating of the various switching devices during nominal operating conditions and during idling. The strategies that are underdeveloped to implement this will be verified using computer simulations.

Power Circuit Design

The design of the power circuit involves careful selection of power semiconductor devices, capacitors, gating systems, electrical interconnections, thermal management, mechanical packaging. The design depends on estimation and determination of worst case and nominal operating conditions and projected lifetime. These design models are under development and will be completed to develop a complete final design suitable for prototype development.

6
CONCLUSIONS

Solid state LTC devices have a number of operating advantages that make them attractive compared to their classical counterparts. Still, the development of a commercially viable solid state LTC has been elusive due to issues related to reliability of application of power semiconductors in the LTC during normal operation, particularly exacerbated by the stresses in the power semiconductors during system faults.

The classical circuit applications incorporating thyristors do not provide the capability to address the fault management issues in a systematic manner, other than unreasonable derating, that lead to uneconomic and ineffective solutions. In this work, the application of a novel and modern matrix switch configuration is proposed.

This circuit configuration applies the switching devices in conjunction with capacitors, and realized as series strings for connection to each of the taps. The configuration has the potential to accommodate n+1 redundancy as well as self-fault current limiting by design and operation. Preliminary investigations of a candidate design based on the specifications of a commercial resistive type LTC have been conducted using computer simulations. The simulations indicated excellent steady state operational performance.

Operational details during faulted operations and detailed designs of the power switching circuits are continuing and will be documented further in the final report for the project in the near future.

A
REFERENCES

1. Evaluate Solid State LTC Options for Medium Power Transformers: Project 41C3084/6658-6424, EPRI, Palo Alto, CA: 2000. 1000916.
2. “IEEE standard requirements for load tap changers,” *IEEE Std C57.131-1995*, Sep 1995.
3. Harlow, J.H., Electric power transformer engineering, 2nd edition, CRC Press, 2007. ISBN: 0-8493-9186-5
4. “On-load tap-changers, type UZ. User’s manual,” ABB, 1ZSE 5492-154.
5. “Order data sheet explanations for tap-changer type UZ,” ABB, 1ZSC000498-AAN.
6. “On-load tap-changers, types UZE and UZF with motor-drive mechanism, type BUF 3. Installation and commissioning guide,” ABB, 1ZSE 5492-115.

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