Comparison between the ETT and LTT Technologies for Electronic OLTC Transformer Applications

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Keywords

«Black start», «Wind-generator systems», «Medium-voltage», «Thyristor», «Transformer».

Abstract

This paper introduces a novel electronic tap-changer application for renewables with light-triggered thyristors for medium-voltage transformers. The on-chip functionality and the robustness of the thyristor support the applications requirements and lower the effort for control and power electronics significantly.

Introduction

Several concepts for electronic tap changers are known. The concept chosen for this project is based on two groups of switches (valves) (Fig. 1. One phase). One group is connected to transformer taps BCD, and the other group is connected to transformer taps EF. This concept lowers the hardware effort and offers a good voltage control range by smartly combining the taps of both groups [1], [2]. Tap voltages of up to 2.5 kVrms can be switched with existing LTTs.
Since power electronic deals with high energy, the whole system needs to be fail-safe. Independent from the kind of failure, the power stage must enter a safe operating mode. A microcontroller combined with software can fail and is therefore not a good way to keep the system under control during a failure situation. A last border needs to be realized, which has to be very simple and of low complexity. The best solution is realization with self-controlled circuits.

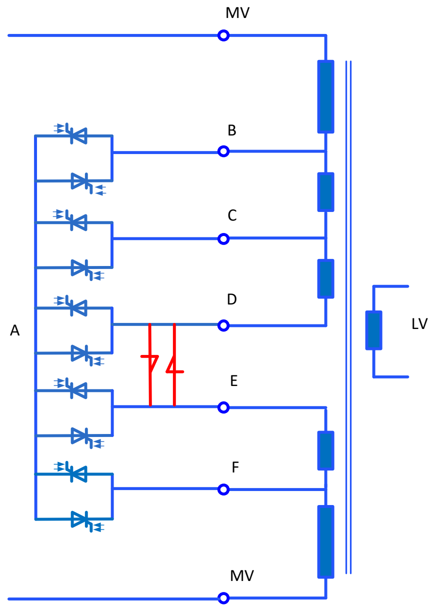


Fig. 1: One phase of the medium voltage transformer with integrated electronic tap changer for 5 taps; and protection circuit colored red.

One critical operation mode is during start-up of a wind-park. In that case medium voltage, Uninterruptable Power Supply (UPS) and control of the wind energy system are down. Once the medium voltage is available, starting up the control system takes approximately ten seconds. During that time, however, the medium voltage transformer is fully powered, but no tap switch is activated. The voltage at the open tap valves will rise to the line side voltage value. That is too much for the tap valves, which are designed for the tap voltage only.
The solution is a self-controlled protection circuit (by-pass for the tap valves) between the two groups of taps (red colored components in Fig. 1.). The self-controlled protection circuit keeps the system in a safe state in case of missing trigger

pulses. The protection circuit is built with two LTTs T533N80 [3]. An optical fiber is not connected, because external triggering is not required. Fig. 2. shows the operation during missing control signals for the tap valves for a 33 kV medium voltage solution. The red colored by-pass circuit (Fig. 1.) turns on at voltage higher than 7.5 kV and keeps the transformer powered up until the regular control takes over. The concept also allows the mandatory lightning test for the transformer without any control electronics. This functionality is supported by the interaction of overvoltage protection, dv/dt protection and the avalanche capabilities of the LTTs chosen. These integrated protection functions have been field tested in many HVDC applications since 2001.

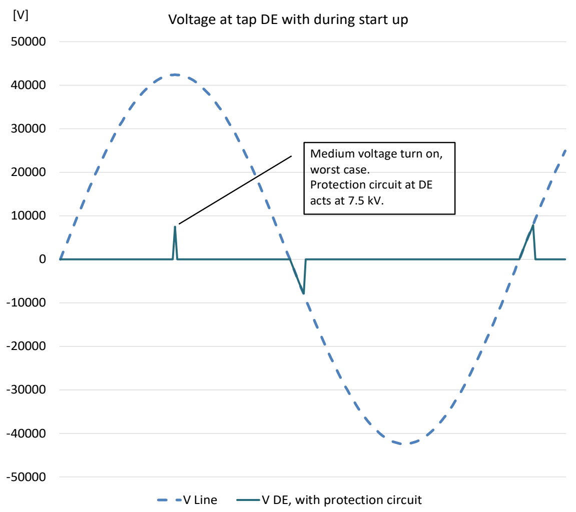


Fig. 2: Voltage at tap DE during operation without control signals for the tap valves.

Application requirements for the power electronics

General design

Since the medium voltage taps of an oil-immersed transformer are located inside the tank, the power electronics also need to be installed inside. That requires that all components of the power electronic stacks to be compatible with the oil chosen. Additionally, the stack materials must not contaminate the oil. That can easily be achieved by using only metals, fiber reinforced plastics (FRP) and PTFE. Furthermore, the whole stack must be able to withstand oil temperatures of up to 120°C.

Design for operation

The tap valves are operated as switches.
Voltage design: The nominal voltage for a valve is equal to the highest tap voltage of 2.4 kVrms. The semiconductor blocking voltage should be, according to the common rules, about 2.4 kVrms * sqrt (2) * 2.0 = 6.78 kV [4]. Furthermore, the stack must be able to withstand, together with the transformer, a lightning test with a peak test voltage of about 170 kV. The tap valves are not triggered during that test. The power electronic stack needs to be protected by internal functionality. Additionally, the valves should work without snubbers. During Black Start the power electronic stack must bypass the tap valves by itself to ensure safe transformer start-up without any external control.
Load-current design: The nominal tap current is around 100 Arms. For the current capability, the individual design and the typical test procedures for medium voltage transformer need to be considered. Consequently, the valves must withstand a short time current of about 2.5 kArms lasting a couple of seconds.

Valve control

Since the power electronic stack is inside the transformer tank on a medium voltage level of e.g. 33 kVrms, the control signals must be isolated accordingly. The isolation rules for the transformer need to be considered. Control signals must be provided optically, due to limited space for bushings on the transformer tank. The control signal needs to be continuous in order to keep the valve capable of being turned on if possible and required. That also makes snubber-less operation possible. Using the common pulse train gate control may cause problems after current zero crossing. Fig. 3. shows the situation during current zero crossing. E.g., V2 is not able to take over the current properly because of the gaps in the control pulse sequence.

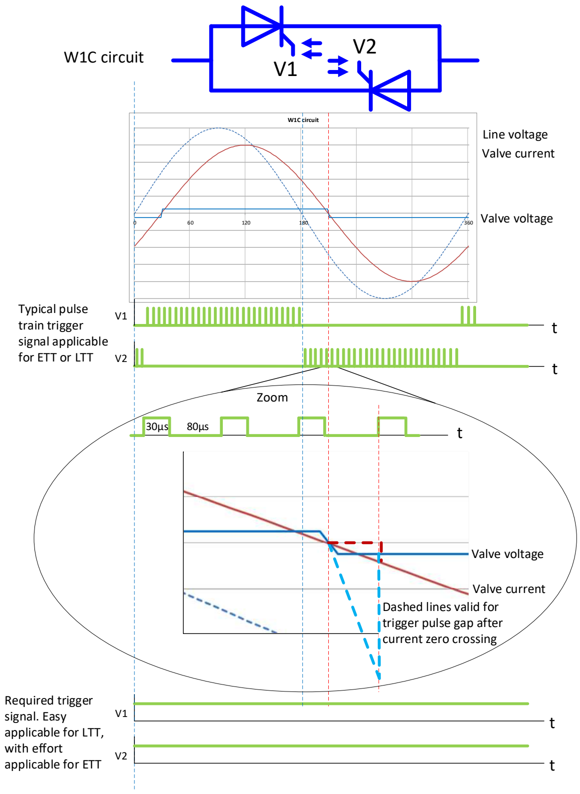


Fig. 3: Voltages, currents and control signals in the W1C circuit with the common pulse train trigger concept.

Besides that, the valves with ETTs require individual trigger signals for V1 and V2, because gate signals are not allowed during negative anode-cathode voltage. LTTs allow simpler continuous trigger signal for both thyristors in a valve. The control signals must not be different. This simplifies the control unit and assures proper current commutation from one thyristor to the other within a valve. Using this concept for ETTs in medium voltage applications requires greater effort because of the required continuous trigger power.

Integrated LTT features

LTTs offer some helpful features for this application. The optical control input, which offers easy medium voltage isolation, eliminates the need for a separate trigger power supply inside the oil-filled transformer. The triggering power is generated on-chip inside the LTT. Furthermore, the on-chip functionality includes an overvoltage and a dv/dt protection (Fig. 4.) (Fig. 8.) (Fig. 9) [5]–[7].

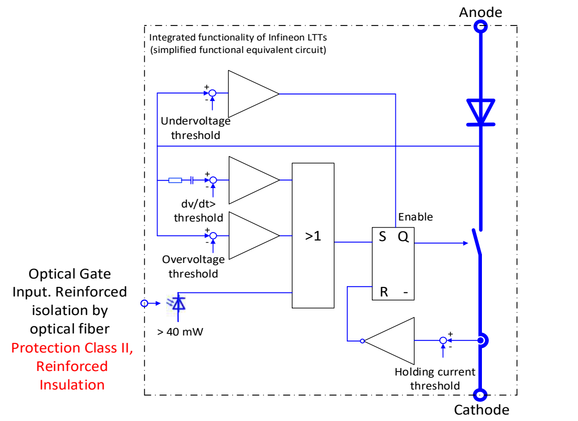


Fig. 4: Functional circuit diagram for LTT T533N80 (equivalent circuit).

Both functions are used for the red colored protection circuit shown in Fig. 1.
A solution with ETT would require a separate active gate driver, an external protection circuit and a trigger power supply system which can operate at up to 120°C installed in the oil tank. Possible variants are described in [8], [9]. The ETT, as described in Fig. 5, does not have its own special functionality [3].

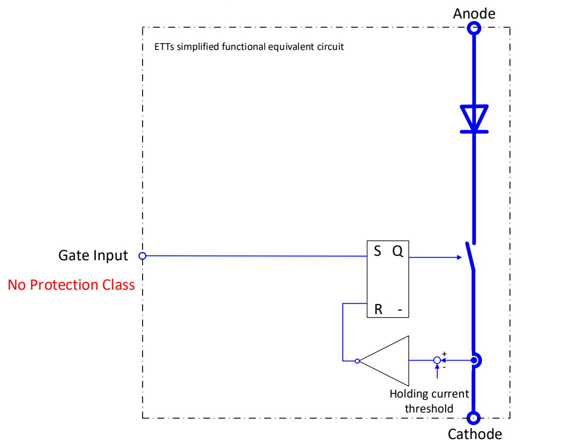


Fig. 5: Functional circuit diagram for ETT T501N70 (equivalent circuit) [3].

In addition to the typical thyristor functionality, functionality also needs to be realized by additional external control circuits and power electronic circuits. Fig. 6. shows an example of the control effort for an ETT solution and Fig. 7. shows the low effort for a LTT solution. The laser diode is installed in the control cabinet, the thyristor in the oil tank. Both are connected via high temperature-capable optical fiber.

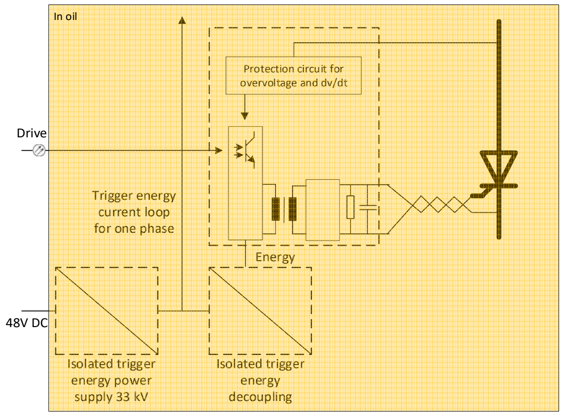


Fig. 6: Trigger circuit effort for an ETT solution. To be installed in hot oil.

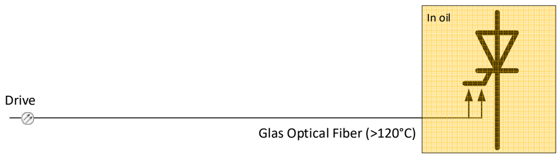


Fig. 7: Trigger circuit effort for a LTT solution. Only the thyristor needs to be installed in oil.

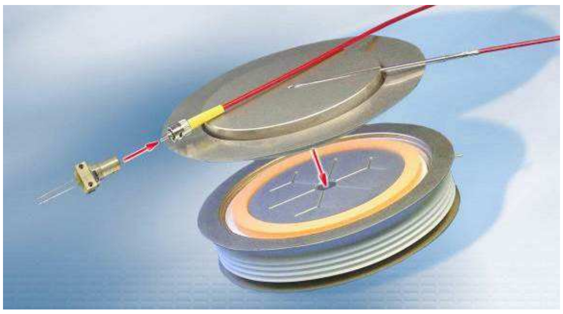


Fig. 8: Light triggered thyristor with integrated functionality (example), optical fiber and laser diode.

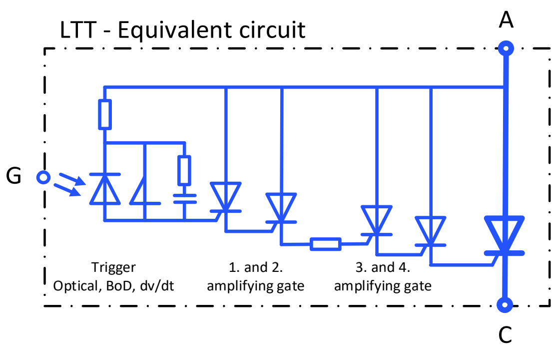


Fig. 9: Equivalent circuit for LTT T533N80 with integrated "on chip" functionality realized by diffusion processing.

Application and power electronic stack design

All thyristors for one phase are assembled in one stack to keep the setup simple and reduce the space requirements inside the transformer. See Fig. 10. The red colored components are the bypass protection components. The attached heatsink increases the cooling capability inside the oil.

Detailed comparison

Functional comparison of possible semiconductor solutions

Table I. shows the advantages of the integrated LTT functionalities for the electronic OLTC. The IGBT is only included to give a full overview of all power semiconductor solutions. A solution with a plastic module in oil is not possible. The LTT solution was realized, and type tested.

Effort comparison for the ETT and LTT circuits

Table II. gives an overview of the materials required for one transformer with 5 taps per phase. Only the LTT solution was realized, because the existing additional components are not compatible with the oil and the oil temperature. A special design is required. Independent of that, the additional components shown in Table II are the typical solution for triggering ETTs in medium voltage applications [10], [11].

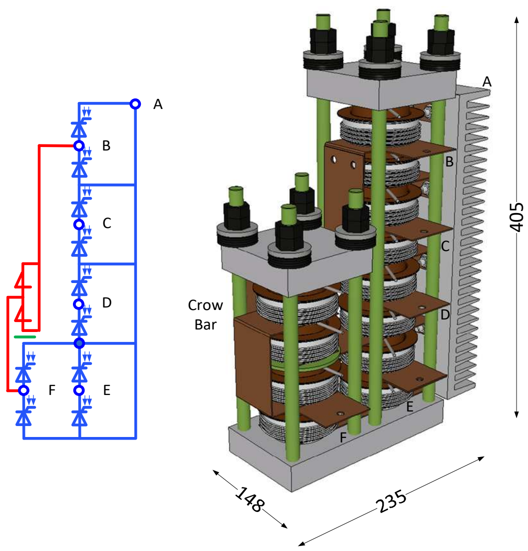


Fig. 10: The press-pack based stack design with 5 taps for one transformer phase.

Fit rate comparison

Transformers are very durable components with a very low failure rate. These properties must be retained when the power semiconductors are introduced. This can be achieved with a small number of extremely robust electronic components. Table III. shows a raw estimation of the FIT rates. It illustrates the vast difference between the two viable solutions.

Comparison of power stack installation

The power electronics needs to be installed in the transformer at the transformer production site. Therefore, the electronic components must fit with the infrastructure and the manufacturing possibilities at that site. Also, the insulation requirements inside of the transformer needs to be considered. The fewer additional components are required, the easier the assembling effort. Table IV. compares the installation effort for the viable power electronic solutions in the transformer.

Table I: Functional comparison of possible solutions.

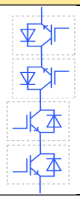
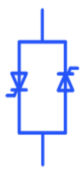
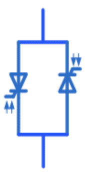
	IGBT	ETT	LTT	Advantage of LTT for the OLTC application
Integrated functionality			**x**	Fewer external components, simple and robust design
Overvoltage protection			x	Offers Black Start ability
dv/dt protection			x	Protection during lightning test
Avalanche capability		x	x	Protection during lightning test
Optical trigger input			x	Isolated input, low trigger power, low power continuous triggering, snubber-less operation
Peak current capability		x	x	Robust against grid and application failures
Power losses	higher	low	low	Transformer with power electronics compliant with EU guidelines
Power components per valve arm	2 in series	single	single	Small number of power components (also valid for ETT)
Valve circuit				Easy setup with isolated trigger input

Table II: Material effort for possible solutions.

Main components per transformer for solution with:		IGBT	ETT	LTT
				
ETT/LTT/IGBT		48	24	24
POF/GOF		36	18	18
LED/laser diode		36	18	18
Additional components for ETT/IGBT				
Trigger Power Supply		3	3	
Decoupling unit		36	18	
Current loop		3	3	
Trigger circuit/gate driver		48	18	
BoD (overvoltage, dv/dt protection)		8	8	
Total main components		218	110	60

Table III: FIT rate comparison for the ETT and the LTT solutions.

Estimated FIT rates for three stacks with 12 thyristors each (5 taps) (e.g.)						
	ETT solution			LTT solution		
Area	Pieces	Single Fit	Total Fit	Pieces	Single Fit	Total Fit
Stack w/o optical fiber:	3	80	240	3	80	240
Thyristor T501, T533:	36	100	3600	36	100	3600
Overvoltage protection (BoD circuits):	6	50	300	0	0	0
Trigger boards:	36	400	14400	0	0	0
Optical Fibers:	30	10	300	30	10	300
Trigger power decoupling unit:	36	50	1800	0	0	0
Trigger power supply:	3	500	1500	0	0	0
LED or Laser in Driver board (per phase):	30	10	300	30	10	300
Total [Fit]:			22440			4440
				Fit rate ratio (LTT / ETT) =		0.2

Table IV: Installation effort for power electronics in the transformer.

Area	ETT (12 per phase)	LTT (12 per phase)	Advantage for:	Benefit:
Specification:	Complete assembled stack weight approx. 22kg.	Complete assembled stack weight approx. 20kg.	LTT	Less weight and easier to handle.
Specification:	Volume of the assembled stack about 25 dm³.	Volume of the assembled stack about 15 dm³.	LTT	Less volume is needed inside the oil tank.
Vapor phase drying (dry type transformer):	Stack, Thyristor, PCBA, trigger connections and trigger transformer must be qualified for vapor phase drying.	Stack, thyristor, optical fiber must be qualified for vapor phase drying.	LTT	Smaller number of parts, which needs to be qualified. Easy to achieve for LTT.
Assembly:	The whole stack with all components (thyristors, PCBA, trigger connections and trigger transformer) needs to be handled during the assembly process.	Only the stack (thyristors and GOFs) needs to be handled during the assembly process.	LTT	An easier stack assembly due to a smaller number of parts.
Trigger signal:	Special oil-resistant material is needed for the trigger circuit PCBA.	Stack and GOFs can be used in oil.	LTT	Smaller size and no additional qualification needed.
Trigger signal:	Thyristor cannot be triggered with simple magnetic trigger transformer. Optical interface required.	Thyristor is triggered directly with signal from optical fiber.	LTT	The LTT trigger circuit consists of standard components.
Trigger signal:	Each semiconductor requires an individual insulated trigger PCBA.	The optical trigger signal input is already insulated.	LTT	Less effort. Easy to install.

Conclusion

The LTT with hermetically sealed press pack ceramics housing, optical triggered gate and the on-chip functionality ensures easy application and proper operation in oil-immersed transformers. The integrated protection functionality makes the LTT solution less challenging in design. The LTT solution has no electrical components beside the thyristors inside the transformer oil tank. The FIT rate for the LTT solution is about 5 times better due fewer components. Only LTT with integrated functionality can support the application needs in a simple manner. The optical gate and the integrated functionality of the LTT reduce external control effort dramatically.

LTTs for electronic OLTC in oil immersed transformers -> low complexity, smart, compact and robust.

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