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Power Electronic On-Load Tap Changer for HVDC Converter Transformer

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Abstract: High voltage DC transmission is gaining more and more importance due to various advantages over high voltage AC transmission. High voltage DC converter transformer is the main component which is used in HVDC transmission. Tap changer is an essential part of any power transformer for obtaining various turns ratios to get different voltage levels. Conventional mechanical tap changers are commonly employed for this purpose. Mechanical tap changers require continuous maintenance when tap changers require frequent operation. The tap changers in high voltage DC converter transformer is such an application where frequent operation of tap changer is needed. In this work a novel power electronic tap changer is proposed for arc less switching and reduced maintenance even under frequent operations. The basic working of the power electronic tap changer, different topologies and certain design parameters of power electronic tap changer for HVDC converter transformer are evaluated and tested using simulation software and a low voltage working prototype.

Keywords: HVDC, Converter Transformer, Tap changer, HVDC Transmission, Tap selector switch

I. INTRODUCTION

High voltage DC transmission is used to transmit electricity over long distances with minimum losses and high efficiency. HVDC transmission is more suitable for bulk transmission of electricity considering affordability and stability [1]. HVDC links are also used to interconnect two different grids which works at two different frequencies. High voltage DC converter transformers are special Electrical Machines which are used for high voltage DC transmission. 16% of total cost for a typical 2000 MW HVDC scheme is for converter transformer [1]. High voltage power electronic converter circuits are used to convert high voltage AC to high voltage DC. A transformer that is used for HVDC conversion is known as HVDC converter transformer [2]. Tap changers are included in this type of transformer to obtain various turns ratio, so that the secondary voltage can be controlled. The reactive voltage drops due to HVDC conversions and voltage drop due to other reasons can be compensated using tap changers [1] [4]. The number of operations of onload tap changer is much higher than conventional power transformer because DC voltage and power flowing through HVDC line is controlled by tap changer [8].

On-Load tap changers are equipped in all higher rating transformers to operate without disturbing the supply. While the No-Load tap changers can be operated only on de-energized condition. Conventionally mechanical tap changers are normally used for this purpose [3]. The available mechanical tap changers are either oil immersed or vacuum circuit tap changers. The conventional mechanical tap changers available in market uses mechanical contacts for switching. The main disadvantage of mechanical tap changer is the slow response and arc formation in the contacts while switching [5] [6]. The arc formation in the contacts reduces the life of tap changers. In addition to this, the arc formation deteriorates the quality of oil used in oil immersed tap changers. So, regular check-ups and maintenance are required for mechanical tap changers. The problems caused by the mechanical tap changers can be overcome by using solid state devices for switching. The advantages of solid-state tap changers are its low maintenance cost, high performance and high operating speed [6].

This paper gives an insight to the principle of operation of solid-state tap changers which can be used in HVDC converter transformer. The research work in this paper mainly focuses on the working of the proposed system, different topologies for the power electronic tap changer, fault in different parts of HVDC transformer and their effects on tap changer. The analysis is done using MATLAB Simulink software. The results of simulation are used for analysing various design problems and hardware implementation of power electronic tap changer for high voltage DC transformer. A low voltage working prototype is made using a transformer, a set of thyristors and an AC to DC converter to analyse and verify the results. To reduce the complexity of calculations and simulation, per phase evaluation is done throughout this work.

II. POWER ELECTRONIC TAP CHANGER

The working of Novel power electronic tap changer for HVDC converter transformer is briefly explained here. The use of power electronic tap changer is more relevant in the case of converter transformers, because it requires frequent operation of tap changers [1]. Periodic maintenance is required if conventional mechanical tap changers are used for this application. Similar to conventional tap changer the power electronic tap changer is also connected on the high voltage side of power transformer to reduce switching on heavy current [4]. It is easy to switch high voltage rather than switching in high current. The power electronic tap changer consists of two antiparallel-connected thyristors which are connected to the respective tap [3] [4] [7]. The particular tap is selected according to requirement by giving triggering pulse to the set of thyristors [6]. The triggering pulses are given to the thyristors at zero crossing point [4]. The thyristor which is forward biased will switch on when triggering pulses are given. Tap selector switch is provided in the tap changers for manual selection of required taps. No two tap selector switches should be operated at a time, if it is operated at the same time, it will cause short circuit of winding and a heavy short circuit current flows through the short-circuited winding. The selection of thyristor is mainly based on the peak inverse voltage (PIV) and current rating of thyristors [1].

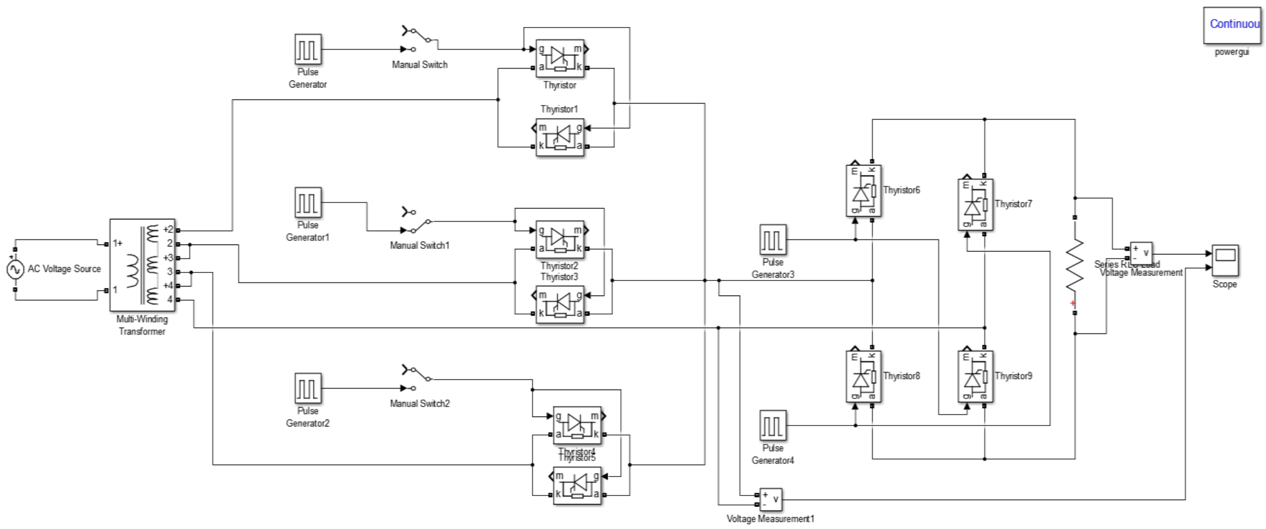

Fig.1 MATLAB Simulink model of proposed System

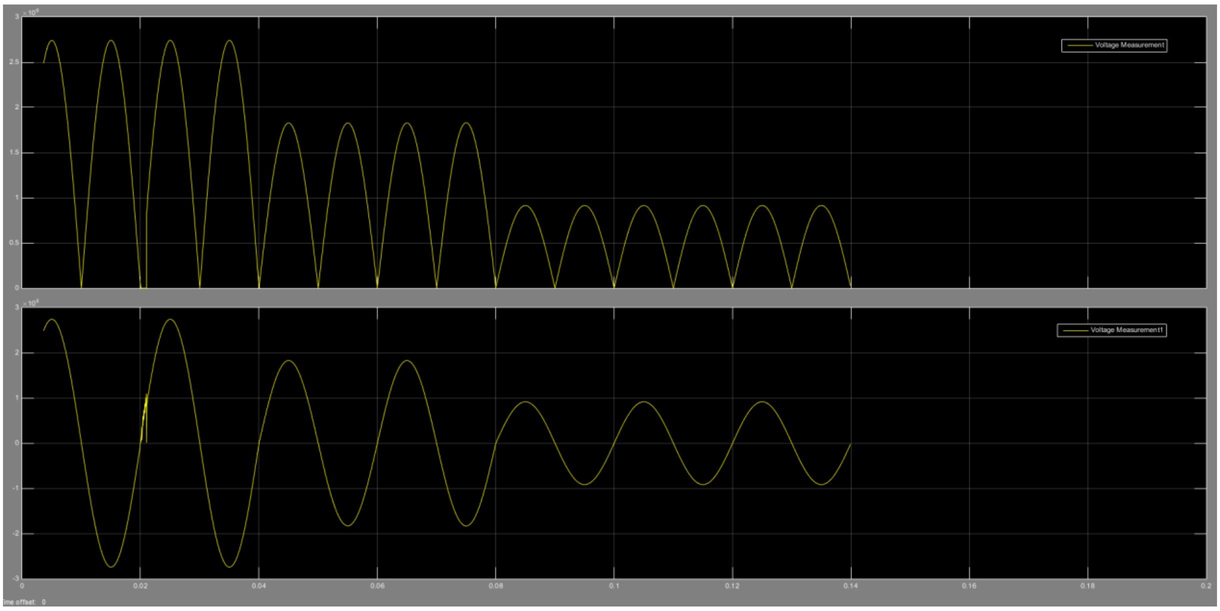

Fig.2 MATLAB SIMULINK model output waveform of proposed system on different tap position

III. DIFFERENT POWER ELECTRONIC TAP CHANGER TOPOLOGIES

Different configurations can be used to design solid state tap changers for HVDC converter transformer. Many topologies are studied to check whether they satisfy the desired requirements. The constraints for designing solid state tap changers for HVDC converter transformers are the cost consideration, harmonic injection to the system, short circuit rating of power electronic components and other power quality issues. Considering all these problems, the most suitable topology is selected for the implementation of the tap changer. Mainly two topologies are evaluated in this work. The power quality issues due to power electronic tap changer can be minimised by using suitable topologies for the tap changer. The topology has also a main role in determining the cost of tap changer.

A. Topology-1

The first topology consists of two-antiparallel thyristors connected to each tap positions. The configuration of this tap changer is similar to that of AC voltage controller. These anti parallel thyristors form a bidirectional switch which ensures the current flow in both directions. The thyristors are triggered at zero crossing points, to obtain a waveform which is closely related to sine wave and to reduce the transients during switching. The output of this configuration is AC and the waveform is continuous in nature.

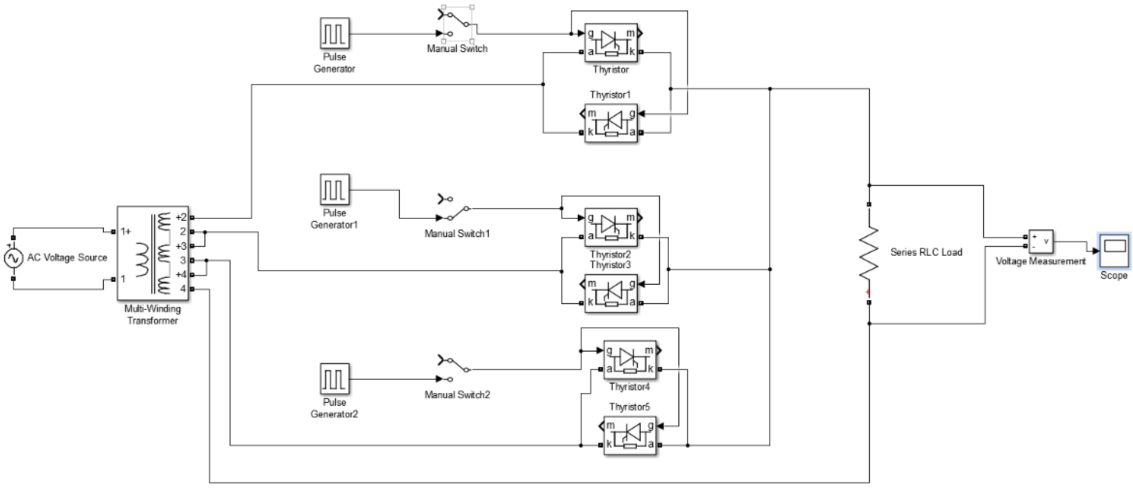

Fig.3 MATLAB SIMULINK model of topology 1

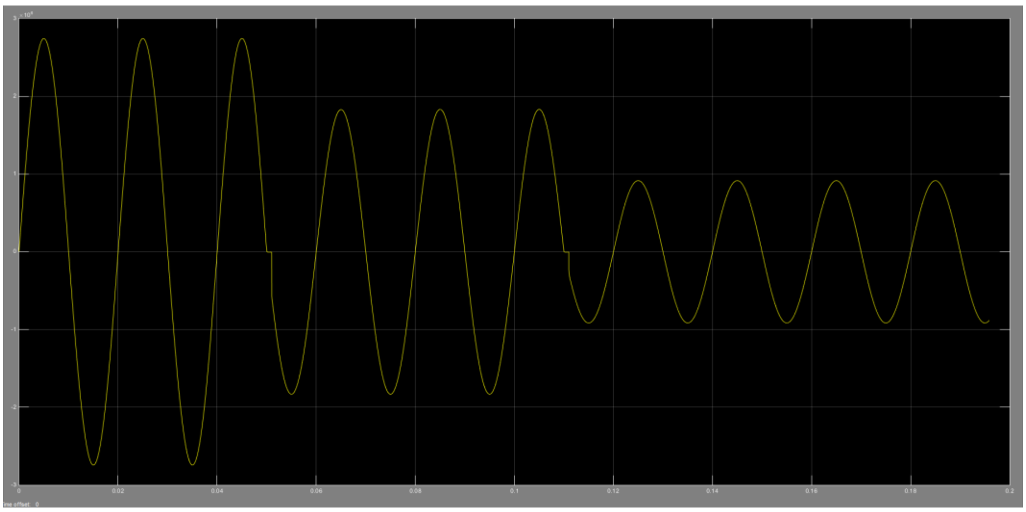

Fig.4 MATLAB SIMULINK model output waveform of topology 1 on different tap positions

This configuration is simulated and various outputs are obtained by varying the tap positions by giving the triggering pulse to corresponding thyristors. This configuration consists of larger number of thyristors so the cost of tap changer is more. The advantage of this topology is harmonic reduction. A separate HVDC converter is required to convert high voltage AC supply to High voltage DC supply. Figure 3 shows the MATLAB Simulink model of the proposed power electronic tap changer topology. The tap changer is connected to a resistive load. The triggering of thyristors are given using pulse generator. The frequency of supply voltage is 50 Hz and the triggering pulse is given to the thyristors at the interval of 10 ms. The thyristor which is in forward biased condition will switched on during the triggering. The switches in the Simulink model will act as tap selector switches. Only one tap selector switch is operated at a time otherwise it will cause short circuit between the transformer winding. Figure 4 shows the simulation output waveform of different voltages obtained at different tap positions. The transients occur during the switching can also be identified from the simulated waveform.

B. Topology -2

The second topology consists of only one thyristor connected to each tap positions. The configuration is similar to that of a half wave diode rectifier circuit. This configuration allows current flow in one direction only. Which means only one-half cycle of an AC supply is conducted through the thyristors. Thyristors are triggered at zero crossing point. The output of this configuration is a pulsating DC, so a separate AC to DC converter is not required in the transformer which uses this topology.

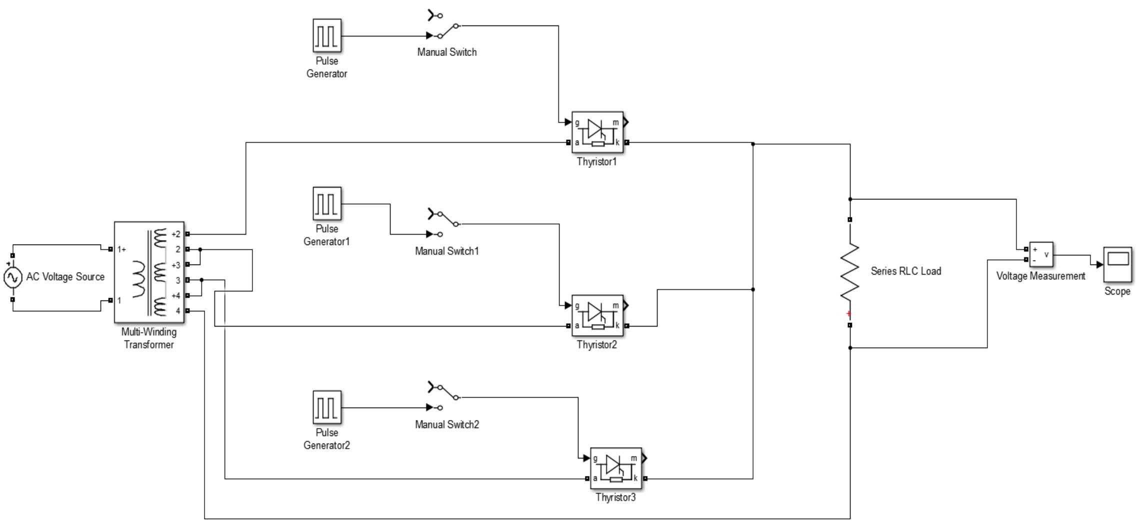

Fig.5 MATLAB SIMULINK model of topology 2

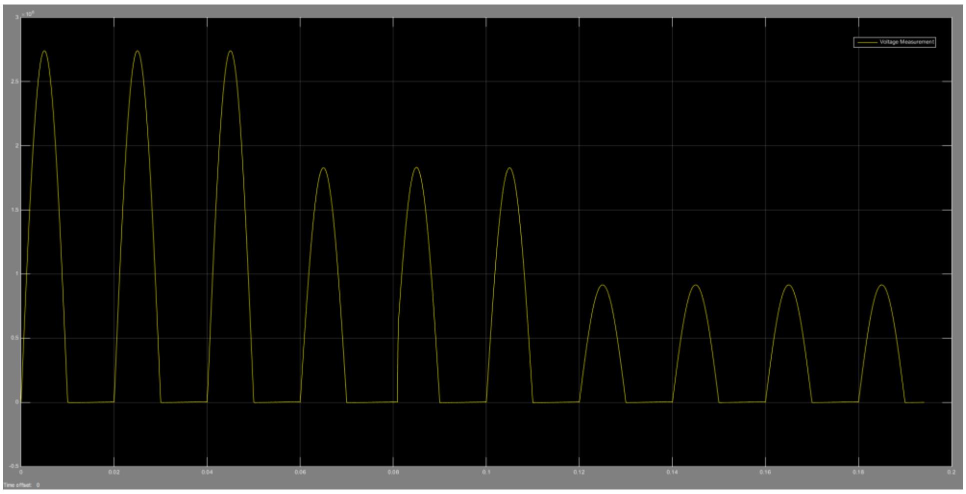

Fig.6 MATLAB SIMULINK model output waveform of topology 1 on different tap positions

The cost of tap changer is also reduced due to a smaller number of thyristors are used in this configuration. The drawback of this configuration is the harmonic distortion and discontinuity in supply voltage waveform. By considering economic aspects of tap changer, this topology can be used. But it is not a feasible solution when the power quality issues are considered. The figure 5 shows the Simulink model of the topology 2. Each tap can be selected using tap selector switches as that is in the previous case. The voltage across the load is measured using a voltage measurement block and its output given to the oscilloscope block. Figure 6 shows the output waveform of topology 2. The voltage waveform at different tap positions are shown in figure 6.

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IV. SHORT CIRCUITS IN HVDC CONVERTER TRANSFORMER AND ITS EFFECTS ON POWER ELECTRONIC TAP CHANGER

Power system components may be subjected to short circuit or other disturbances at any time in its operation. The fault identification and isolation are very much important in the case of HVDC transformer, since a number of power electronic components are involved in the system. The fault current can damage the power electronic components in tap changer and HVDC converter. A fault can occur either in AC Side or DC side. The occurrence of a short circuit in DC side is rare [1]. However, a fault on DC side is simulated and waveform is shown in figure 9 and figure 10. There are no circuit breakers on the DC side of converter transformer [1].

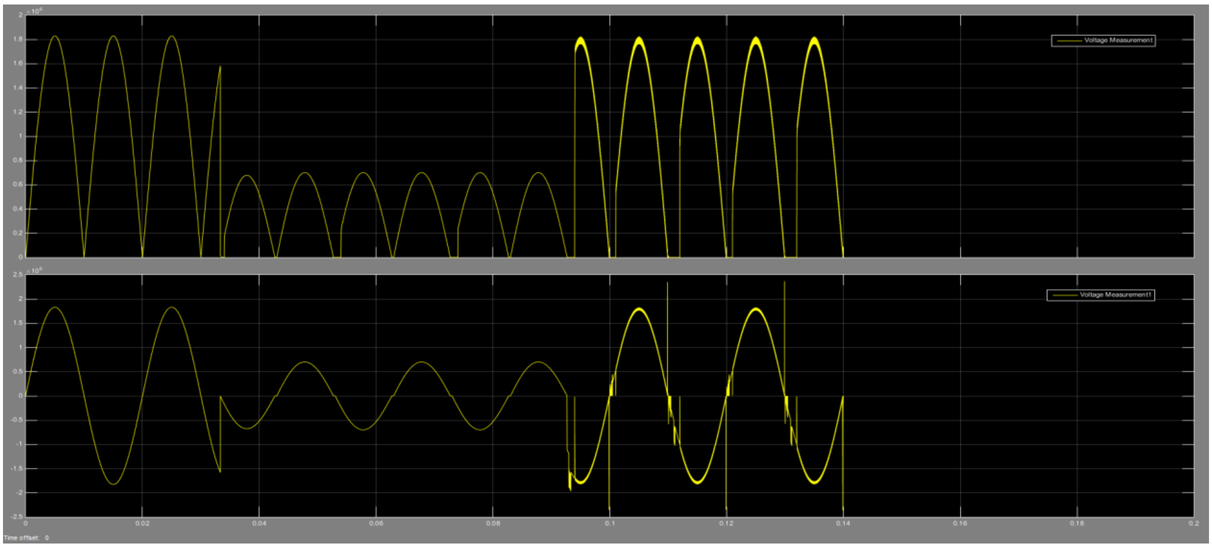

Fig.7 (a) Voltage waveform on DC side when a short circuit fault occurs on the high voltage AC side of transformer (b)voltage waveform on AC side when a short circuit fault occurs on the high voltage AC side of transformer

The fault clearing is carried out by blocking the converter circuit and dissipating the stored energy, so that there is least chance for affecting the faults in DC side to the solid-state tap changer. The usual faults in AC sides are asymmetrical faults and very rarely symmetrical faults. The faults occur in high voltage AC side of the HVDC converter transformer is not severe when compared to other AC systems, Because the load is a HVDC converter and it does not feed any additional current to the fault [1]. The waveform of fault occur in high voltage AC side of a HVDC converter transformer is shown in figure 7 and figure 8. In the case of a fault in AC side the protection can be incorporated in tap changer by blocking the anti-parallel connected thyristors as in DC systems.

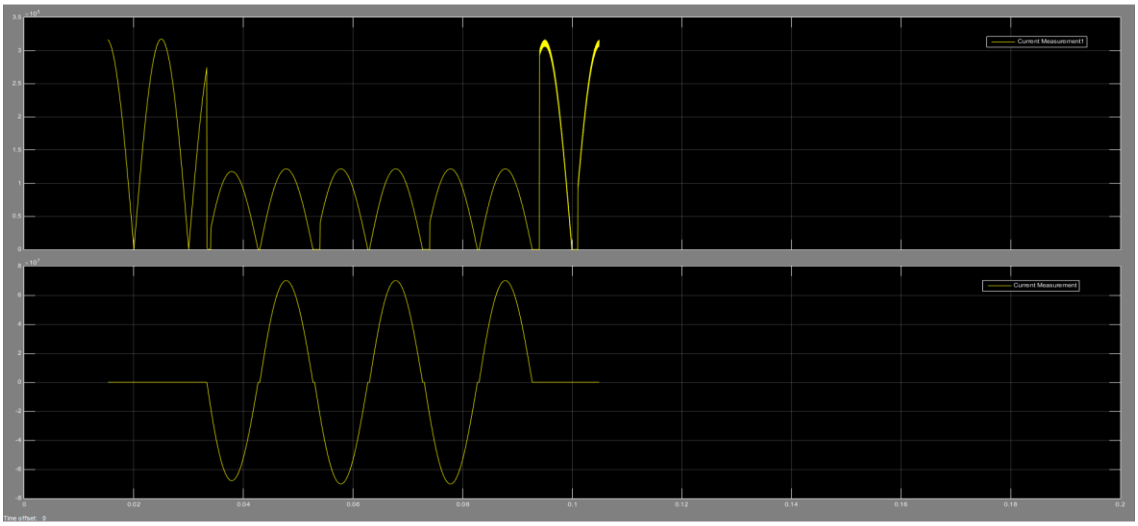

Fig.8 (a) Current waveform on DC side when a short circuit fault occurs on high voltage AC side of transformer (b) Short circuit current waveform when a Short circuit occurs on high voltage AC side of a converter transformer

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Simulations are done by making short circuits in high voltage AC side and high voltage DC side of the transformer. Current and voltage waveforms are analysed in each case. Figure 7 shows the voltage waveforms in AC and DC side when a short circuit fault occurs in high voltage AC side of the transformer. The voltage in the DC side decreases when a fault occurs in AC and DC side of the transformer. Transients can also be identified from the waveform. Figure 8 shows the current waveform in AC and DC side when a fault occurs on high voltage AC side of the transformer. Figure 8(a) is the current waveform obtained by measuring the current through the load. It is identified that current flow through the load decreases when a fault occurs on the high voltage AC side of the transformer. The figure 8(b) is the short circuit current waveform obtained during short circuit on the AC side of the transformer. Figure 9 shows the voltage waveforms obtained when a fault occurs on high voltage DC side of the transformer. As in figure 9(a) there will be a dip in voltage on the DC side when a fault occurs on the HVDC side of the transformer.

As shown in figure 9(b) voltage distortions and voltage dip happen when a fault occurs on HVDC side of the transformer. Figure 10 shows the current waveforms obtained when short circuit fault occurs on the High Voltage DC side of HVDC transformer. Figure 10(a) shows the current waveform of short circuit fault and figure 10(b) shows the current flows to AC to DC converter when a short circuit fault occurs on the DC side of the transformer. From wave form analysis it is evident that the short circuit occurring on the high voltage AC side is more affected to the power electronic tap changer than the fault occurring on high voltage DC side.

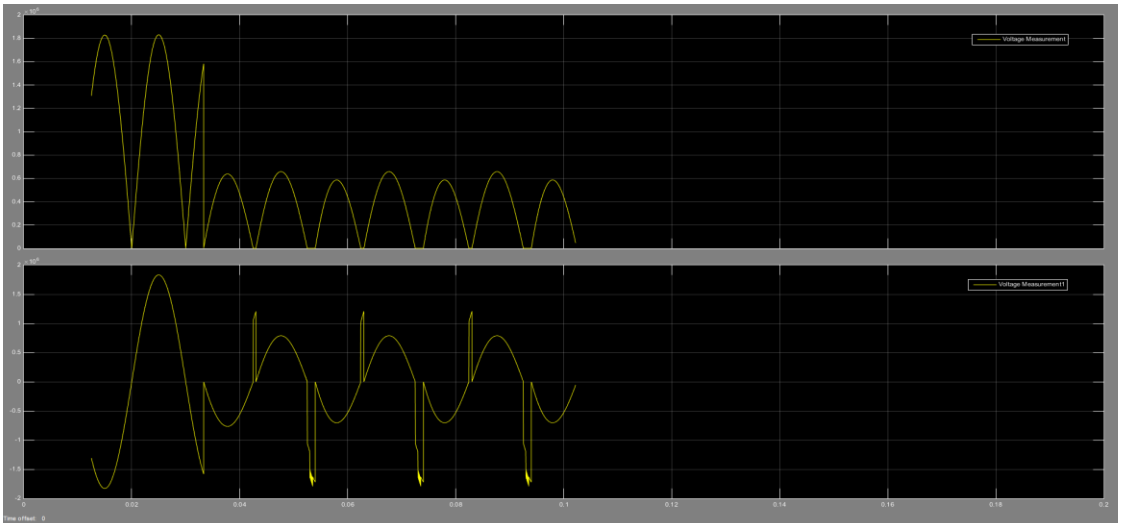

Fig.9 (a)Voltage waveform on DC side when a short circuit fault occurs on high voltage DC side of transformer
(b) Voltage waveform on high voltage AC side of transformer when a short circuit occurs on high voltage DC side of transformer

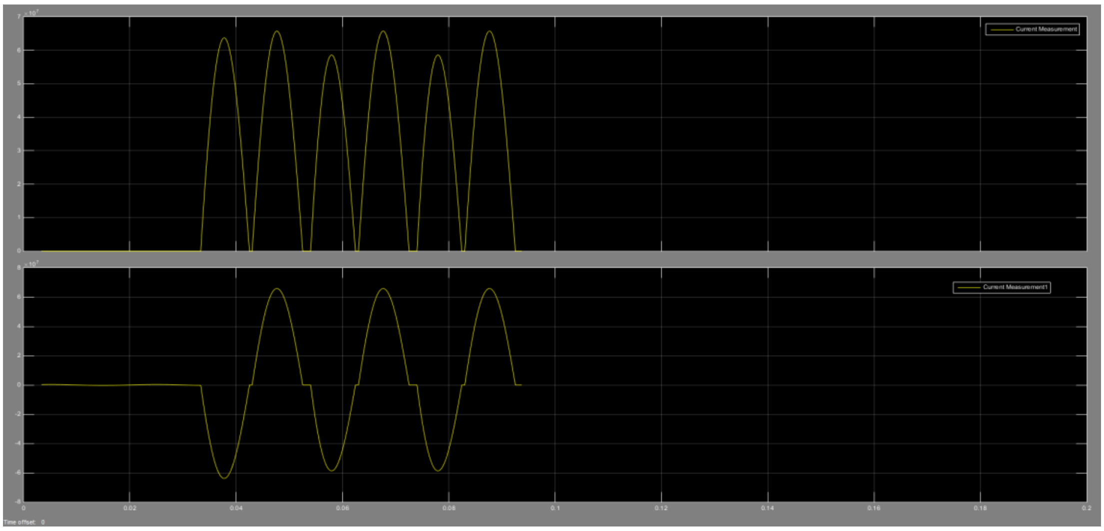

Fig.10(a) Current waveform on DC side when a short circuit occurs on high voltage DC side of transformer
(b) Short circuit current waveform when a short circuit occurs on high voltage DC side of transformer

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V. WORKING OF PROTOTYPE

A low voltage prototype is made for experimental purpose. A single phase 150 VA step down transformer is designed and waveforms at different tap positions are analysed using an oscilloscope. The rated primary voltage of transformer is 240 V and the secondary voltages at different positions are 30 V,24 V,18 V,12 V and 6 V. The secondary current of the transformer is 5A. AC to DC converter is a bridge rectifier using diodes. A resistive load is connected to the converter transformer. Voltage across the load is measured using a digital voltmeter. TYN616 thyristors are used as switching devices. The triggering of the antiparallel connected thyristors is done using tap selector switches.

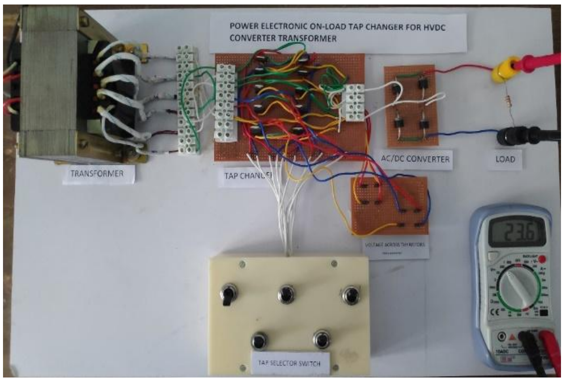

Fig.11 Working Prototype

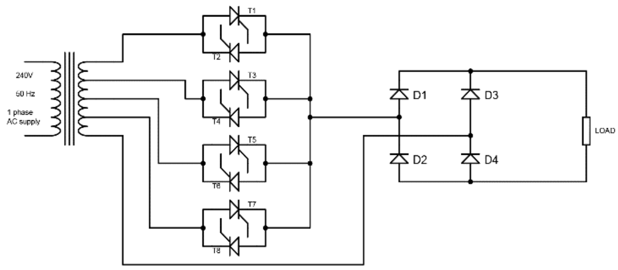

Fig.12 Circuit Diagram of prototype

In low-voltage prototype, the thyristors are connected in the low voltage side of the transformer to reduce complexity in design and for taking measurements using low voltage measuring instruments. Different taps can be obtained by using tap-selector switches. The transformer is designed in such a way that it can withstand the heating due to harmonic currents flows through winding of transformer. The figures 13, 15 and 17 shows the output waveform of the transformer at different tap positions. Figure 19 shows the voltage across thyristors during operation. Figures 14, 16 and 18 shows the voltage across the load at different tap positions.

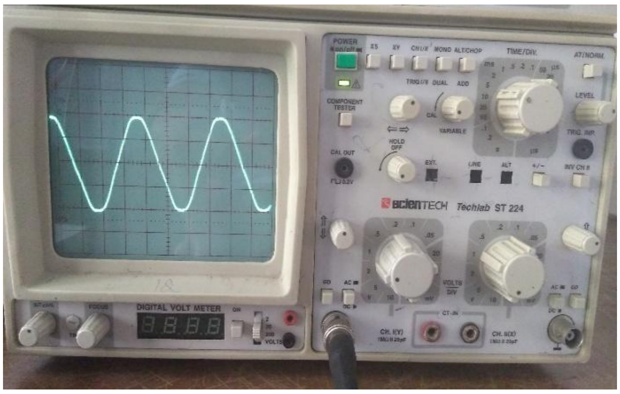

Fig.13 Output of transformer at Tap position 1

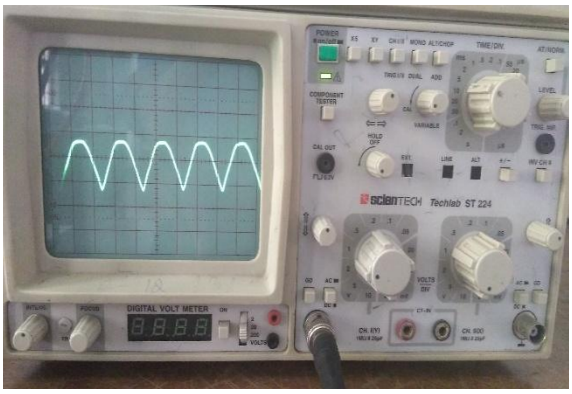

Fig.14 Output across load at Tap position 1

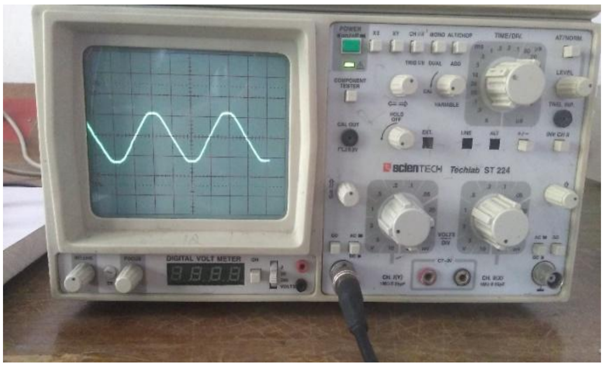

Fig.15 Output of transformer at Tap position 3

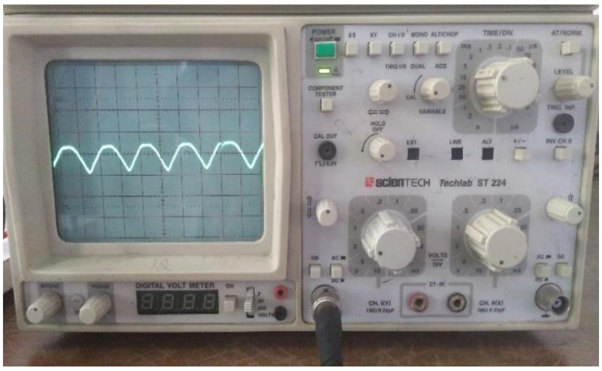

Fig.16 Output across load at Tap position 3

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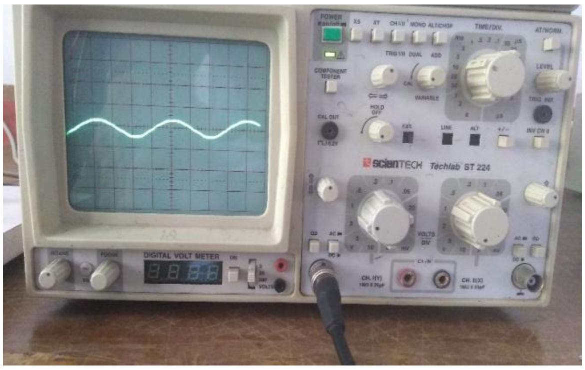

Fig.17 Output of transformer at Tap position 5

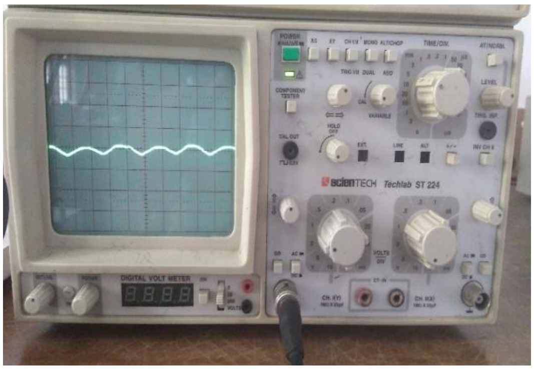

Fig.18 Output across load at Tap position 5

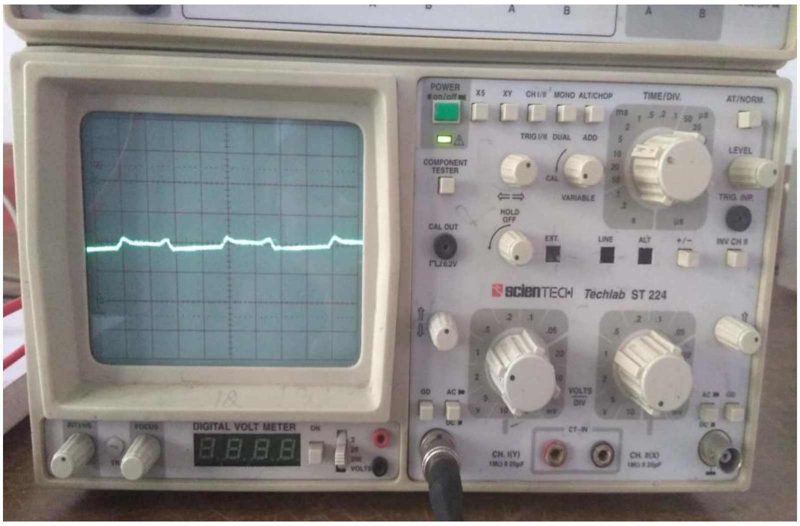

Fig. 19 Voltage across thyristors during on condition

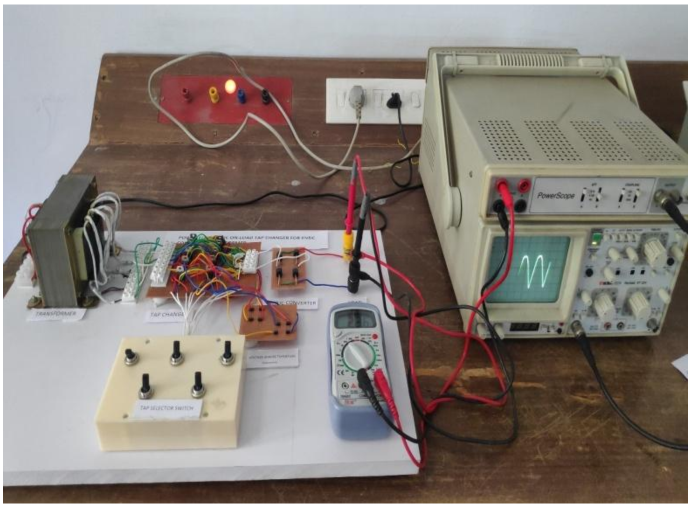

Fig.20. Experimental Setup used for analysis

VI. CONCLUSION

In this work a novel solid-state tap changer is introduced for high voltage DC converter transformers. The high voltage converter transformer requires wide range of voltage control over conventional power transformer. The solid-state tap changers have many advantages over mechanical tap changers. The advantages include fast operation, less maintenance, no switching arc, no moving contacts etc. The main design criteria of the solid-state tap changer are its short circuit rating and peak inverse voltage across the power electronic switches. The short circuit rating of power electronic tap changing switches can be improved by using more numbers of switches in parallel and the voltage rating can be improved by connecting a number of power electronic switches in series. The fault isolation of the high voltage AC side of the transformer can be done by blocking the power electronic switches, so that protection can be ensured and circuit breakers in high voltage AC side of the transformer can be eliminated. The main disadvantage of the solid-state tap changing is the power quality issues. Harmonic injection is the major power quality issue which affect the transformer. The circulating harmonic current through the winding can cause additional heating. So, the K rating of the HVDC transformer will increases when power electronic tap changers are used. The harmonic issues can be reduced by using better topology for the design of tap changers and by using modern power electronic switches which has the advantages of less switching speed. The special harmonic filters can also be designed for reducing harmonic currents that affect the HVDC transformer due to power electronic tap changer and HVDC converter which is connected in high voltage AC side of the transformer. A preliminary work which contains the basic working and main design aspects are described in the paper. The practical implementation of this needs more study and analysis.

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