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DOI
10.1109/EPEPEMC.2014.6980624

Publication date
2014

Document Version
Accepted author manuscript

Published in
Proceedings - 2014 16th International Power Electronics and Motion Control Conference and Exposition

Comparative analysis of On-Load Tap Changing (OLTC) transformer topologies

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***Abstract* — On-load tap changing (OLTC) transformers are widely used for voltage control in the distribution network. The paper provides a comparative analysis of different OLTC topologies for the design of a power electronic (assisted) tap changer. Eleven different topologies are compared on the basis of voltage and current rating of the transformer windings and tap switches, using a p.u. methodology. The topologies are designed in such a way that they can provide both positive and negative compensation of the grid voltage. The p.u. comparison is a beneficial tool for OLTC designers to suitably choose the right topology based on the voltage and power levels of the network, type of solid-state switch used and the voltage regulation application.**

Keywords — compensation, on-load tap changer, transformer, voltage control

I. INTRODUCTION

On-load tap changing transformers (OLTC) are widely used for voltage control in the distribution network [1-5]. OLTC compensate the voltage drop/gain along the distribution feeders to keep the load voltage within the nominal range. Three different types of OLTC are present – mechanical tap changers, solid state (power electronic) tap changers and power electronic assisted tap changers [2-9]. Conventional OLTC use mechanical switches for taps which undergo wear and tear during the tap change operation due to occurrence of an arc [2-4]. Solid state tap changers and power electronic assisted tap changers, on the other hand use semiconductor switches during the tap change process which results in an arc-free tap change [4-9].

In recent years, there has been a large scale integration of distributed generation (DG) especially PV in the distribution network and it is only expected that this situation will increase in the near future. The DG power injection has led to frequent voltage fluctuations and overvoltage in the distribution network [10-13]. Conventional OLTC are unable to cope with this situation due to frequent tap changes and repeated degradation of the mechanical taps due to arcing. This necessitates frequent maintenance and increased operating cost. The solution for the future hence lies in utilizing power electronic (assisted) tap changers or tap changers using vacuum switches which have no/reduced arcing during tap changes [14]. The focus of this paper is to analyze and compare different OLTC topologies that can be used to build power electronic (assisted) tap changers.

Power electronic OLTC transformers can be built using conventional two-winding transformers or auto transformers. The cost and material required for the OLTC depends mainly on the following five factors:

1. OLTC is built using a two-winding transformer or an autotransformer.
2. Nominal voltage and current rating of the transformer windings.
3. Number of taps/semiconductor switches.
4. Nominal voltage and current rating of the semiconductor switches.
5. Fault conditions in the network, protection and control.

The aim of this paper is to compare different OLTC topologies on the basis of the first four factors listed above assuming that the same fault conditions in the network and necessary protection mechanism are applicable to the different topologies. The findings of the paper provide a useful tool for OLTC designers to choose the right topology for the solid state OLTC based on the component ratings, application and voltage regulation requirements.

Firstly, the fundamentals of the two transformer types namely the two-winding transformer and autotransformer are analyzed in section II. In the next section, the various tap changer topologies that use both types of transformers are introduced. Subsequently for each topology, the ratings of transformer windings and switches are estimated analytically and verified using PLECS simulations. Finally, the topologies are compared on the basis of component ratings elucidating the advantages and disadvantages of the designs.

II. CONVENTIONAL TWO-WINDING TRANSFORMER & AUTOTRANSFORMER

Fig. 1 shows an ideal two winding transformer with the primary high voltage winding (*HV*) and the secondary low voltage winding (*LV*) [15, 16]. If taps were present on the secondary side and tap position is given by x:

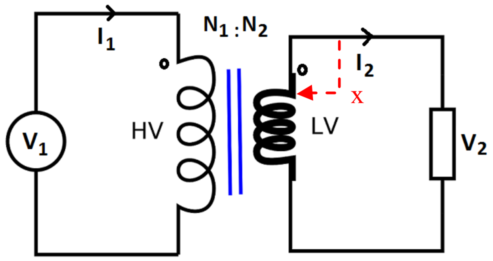


Fig. 1. Ideal two winding transformer

$$V_2 = \left(\frac{V_1}{N_1}\right)x \qquad I_1 = \left(\frac{I_2}{N_1}\right)x \tag{1}$$

Thus by varying the tap position x, a variable voltage at secondary can be obtained by using a fixed voltage at the primary side.

A more compact and cost effective solution to obtain a variable secondary voltage is by using an autotransformer [2-4, 15, 16]. Fig. 2 shows the schematic of an autotransformer where the two windings of a conventional transformer *HV* and *LV* are electrically connected. By varying the connection of the source and load across *HV* and *LV*, the two different modes of operation can be obtained – buck mode and boost mode.

For autotransformers, the power transferred at the terminals of the transformers *S(Through put)* is much higher than the power transformed through the core by magnetic action *S(Transformed)* [16]. This is due to the electrical connection between the input and output, so majority of the power is directly transmitted and not magnetically. The capacity multiplication factor F_c is defined as the ratio of power transmitted through the terminals of the autotransformer namely *S(Through put)* to the power that is magnetically transformed through the core namely *S(Transformed)*, where $r=V_2/V_1$ [16]:

$$\text{For Boost mode, } F_c = \frac{r}{r-1} \tag{2.1}$$

$$\text{For Buck mode } F_c = \frac{r}{1-r} \tag{2.2}$$

For a conventional two-winding transformer, F_c =1. For an autotransformer, if *HV* primary winding is rated for 1p.u. voltage and the *LV* secondary is rated for 0.1p.u. voltage, F_c would be approximately 10 (F_c*=11, r=1.1* for boost mode; F_c*=9, r=0.9* for buck mode). Thus ten times more power can be transferred across a conventional transformer if it were operated as an autotransformer. This higher power transmission capacity of autotransformer comes at the cost of lack of magnetic isolation between the input and output.

In an autotransformer, part of the input winding *HV* is common to the output as well. This results in copper savings, which can be estimated by C_r=(Copper used in autotransformer ÷ Copper used in two winding transformer) [16].

$$\text{For Boost mode, } C_r = \left|1 - \frac{N_1 + N_2}{N_1}\right| \tag{3.1}$$

$$\text{For Buck mode } C_r = 1 - \frac{N_1}{N_1 + N_2} \tag{3.2}$$

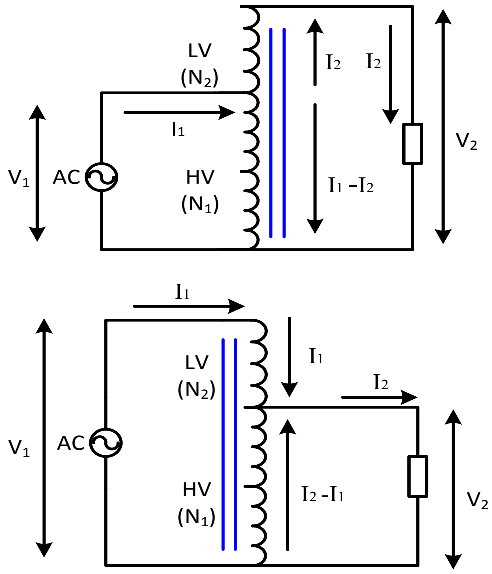


Fig. 2. Autotransformer in boost (top) and buck (bottom) operation

For small values of N_2, the savings are maximum. For small compensation up to 10%, $N_2 = 0.1\ N_1$ and C_r = 10%. So the autotransformer will require only 10% of copper as required by a full transformer for same *S(throughput)*.

It can thus be concluded that for voltage regulation applications where voltage ratio V_2/V_1 is close to 1 and isolation is not required, an autotransformer is the preferred choice over a conventional transformer due to the higher throughput power and copper savings.

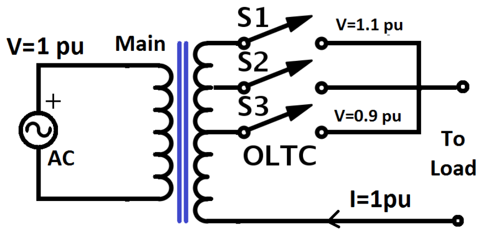
III. OLTC Topologies

Through the use of conventional two-winding transformers and autotransformers, different configurations of a single phase OLTC transformer can be achieved. The objective is to feed a series compensating voltage of up to ±10% of the nominal voltage in *N* steps through the transformer taps. The assumptions made during the design of the topologies are:

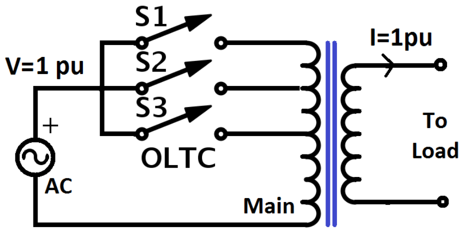
- The transformer and switches are assumed to be ideal with no leakage and parasitic impedance
- 1p.u. is set as the rated load current and rated source voltage. Thus the rated load power will be 1p.u.
- Tap switches must be able to block bidirectional voltages and conduct bidirectional currents
- Each transformer tap provides 2% compensation. For providing full ±10% compensation, a total of 2*(10% / 2%) = 10 taps will be required (*N=10*)

A. Topology 1 and 1a

Topology 1 and 1a uses a conventional two winding transformer of 1.1p.u. power rating with the taps positioned either on the primary or the secondary windings as shown in Fig. 3 [2, 5, 15]. The topology provides complete isolation between the input source and the output load. It can provide both positive and negative compensation in *N* steps. (*2N+1*) taps will be required, where *N* taps are used for positive



Turn ratio = 10 : 11



Turn ratio = 11 : 10

Fig. 3. Topology 1 (top) and 1a (bottom) using a conventional two-winding transformer

compensation, N taps for negative compensation and an additional tap for 0% compensation. In 1, the major disadvantage is that the tap switches are not isolated from the load and directly exposed to secondary side fault current. For topology 1, depending on the tap position, x can range from $x=0.9N_1$ to $x=1.1N_1$ (see Eqn. (1))

Due to the asymmetry in the arrangement of taps, the maximum forward and reverse blocking voltages of the tap switches are not the same for all taps and differs based on the tap position. For both *1* and *1a*, when the one of the switches is conducting, the other switches will have to block voltages up to V_b=0.2p.u., depending on the switch position. V_b is the blocking voltage rating of the switches as mentioned in Table 2, where both the forward and reverse blocking voltage of the switches are listed in the form (x, y). Values referred as (x, y) indicate that depending on the tap position, the tap switch is rated for blocking voltage in the range of 'x to y' for tap switch S1 to S3 respectively.

When all taps are open in topology 1, the forward blocking voltage required for the tap switches will range from 0.9p.u. to 1.1p.u. for S3 to S1 respectively. This indicates the necessity to keep at least one tap switch in ON condition always [17]. A protective device for protecting the electronic switches from fault conditions should be integrated [18]. This will ensure that the maximum voltage on the switches is restricted to 20% (0.2p.u.) of the nominal grid voltage.

For *1a*, the maximum voltage on primary winding $V_{1\ MAX}$ is 1.22p.u. when S3 is ON. When all the switches are in OFF condition they must be able to withstand a forward blocking voltage of 1p.u. as they are connected to same source voltage. The voltage V and current I ratings of transformer are summarized in the Table 1, where *1"* and *2"* refers to the primary and secondary winding respectively. The switch blocking voltage V_b and current ratings I are summarized in Table 2. The voltage and current ratings in both tables are verified in PLECS® software as shown in Fig. 4. The PLECS

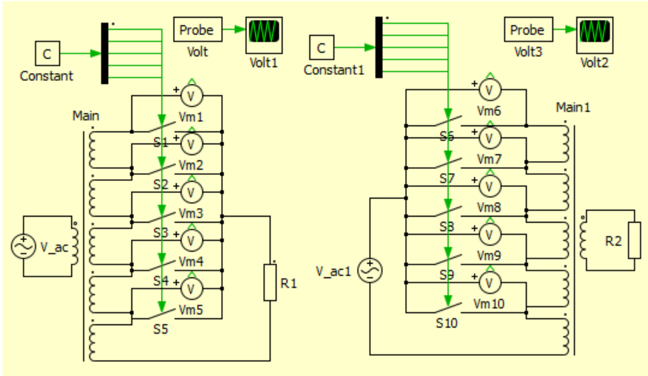
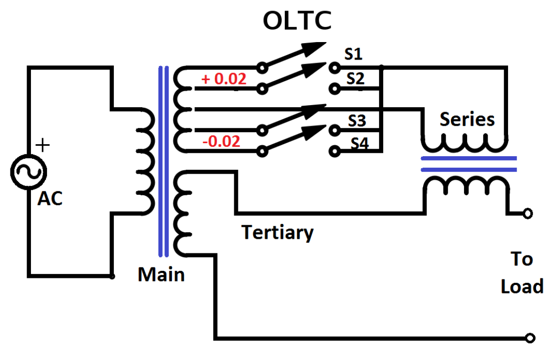


Fig. 4. Simulation model of topology 1 and 1a in PLECS software



Turn ratio = 10:10:2 (Main) & 1:1 (Series)

Fig. 5. Topology 2 implemented using a three-winding transformer and a series transformer

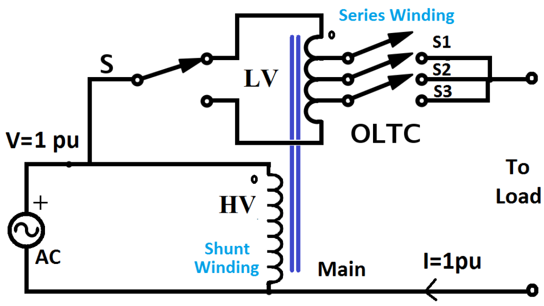
verification is performed for all subsequent topologies as well.

B. Topology 2

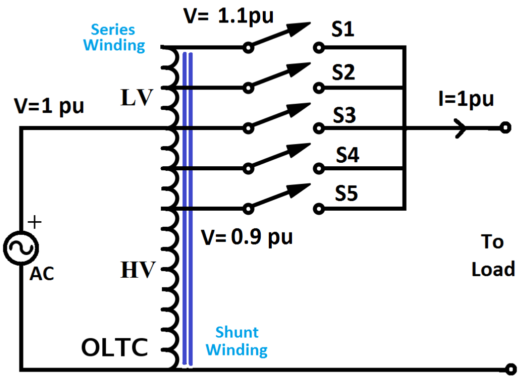
Topology 2 is shown in Fig. 5. The main transformer is a three winding transformer of 1.1p.u. power rating with a turn ratio of 10:10:2. The secondary winding of the main transformer has taps and the compensating voltage is fed in series to the grid voltage using a series transformer of 1:1 turn ratio. The tertiary winding of the main transformer provides the load power and is rated for 1p.u. voltage and 1p.u. current. The use of two transformers makes the design very expensive, but ensures that the switches are isolated and so are the source and load. When one of the taps is conducting, the other tap switches have to block 0.2p.u. to 0.1p.u. voltage depending on their position. The tap switches are rated for 1p.u. load current. The design ratings are summarized in Table 1 and Table 2.

C. Topology 3 and 3a

Topology 3 shown in Fig. 6 corresponds to the conventional voltage regulators [2-4, 13]. that are utilized in the grid It consists of an autotransformer with taps on the series winding *LV*. A selector switch *S* connects either the top or the bottom of the series winding *LV* to the primary winding *HV* so as to provide negative or positive compensation respectively. The benefit of this topology is the reduction in the number of switches by half to *(N+1)+1*, where *(N+1)* corresponds to the tap switches and *+1* for the selector switch *S*.

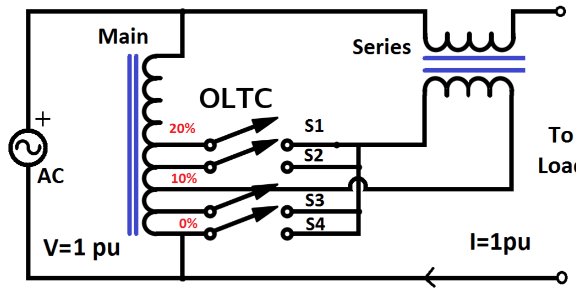


Turn ratio = 10 : 1

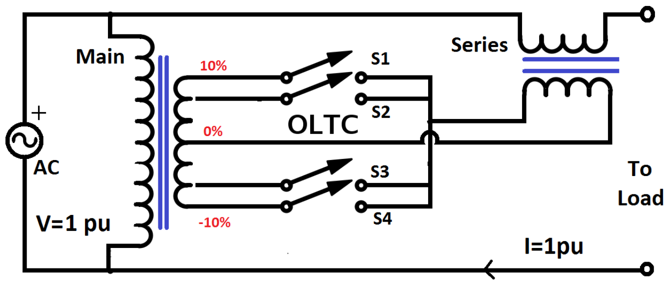


Turn ratio = 9 : 2

Fig. 6. Topology 3 (top) and 3a (bottom) built using an autotransformer. Topology 3 uses a selector switch that determines the sign of voltage compensation.



Turn ratio = 8:2 (Main) & 1:1 (Series)



Turn ratio = 10:2 (Main) & 1:1 (Series)

Fig. 7. Topology 4 (top) and 4a (bottom) built using a main and series transformer. Topology 4 uses an autotransformer for the main transformer while 4a uses a conventional two winding transformer.

In contrast, topology 3a shown in Fig. 6 does not have a selector switch S and has a total of *(2N+1)* tap switches. The primary input winding *HV* is rated for 0.9p.u. voltage and is permanently connected to the series winding *LV* that has taps on it and is rated for 0.9p.u. voltage.

Depending on which tap is ON, the non-conducting tap switches have to block up to 0.1p.u. voltage for topology 3 and up to 0.2p.u. voltage for topology 3a. When the selector switch is ON in topology 3, it must block ±0.1p.u.voltage between the input and unconnected output terminal. The selector switch has to be rated for carrying the full load current of 1 p.u. This is a vital consideration in the design of the selector switch. Table 1 and 2 lists the design ratings of the transformer and switches.

Comparison of different OLTC topologies from this paper was used in [9]. Topology 3 was chosen as the most suitable design for that application due to the use of an autotransformer, low voltage ratings of tap switches and simple operation mechanism.

D. Topology 4 and 4a

Topology 3 and 3a have the drawback of the switches not being isolated from the load. Topology 4 shown in Fig. 7 combines the benefits of using an autotransformer in buck mode and the need to have isolation for switches through a series transformer [3, 19]. Here the compensation voltage is derived from the grid voltage through the use of an autotransformer tapped at 0% and 20% points and a center tap at 10%. *(2N+1)* switches are required for the operation, half for positive and rest for negative compensation. Topology 4a is similar to 4, however a two-winding transformer is used which provides isolation of switches from source side as shown in Fig. 7.

The sizing of switches for 4 and 4a is similar to topology 2. The transformers have a reduced power rating of 0.1p.u. as it handles only the compensating power. If all the switches are in blocking state and no compensating voltage is being fed to the grid, the series transformer operates in a reverse fashion and uses the grid voltage as input and imposes it onto the switches. In such a scenario, voltage of up to 1.1p.u. must be blocked by the tap switches.

E. Topology 5 and 5a

The use of a selector switch was shown to reduce the total number of switches by half as in topology 3. The same technique is implemented in case 4 and 4a, to give topology 5 and 5a [2, 3, 15], shown in Fig. 8. For topology 5, the taps are present on 0% to 10% section of the autotransformer windings. The position of the selector switch determines the sign of compensation – for e.g. positive voltage is injected when S is in the 10% position of the winding as shown in Fig. 8. The maximum switch blocking voltage required when one of the tap is ON is 0.1p.u. - this value is half of what was observed in topology 4 and 4a. The selector switch blocking rating is also ± 0.1p.u. voltage and 1 p.u. current.

Topology 5a is similar to 5, but uses a two winding transformer with taps for the main transformer instead of an autotransformer. The component ratings for both topologies are similar and are summarized in Table 1 and Table 2. The only differ in the voltage and current ratings of the transformer windings.

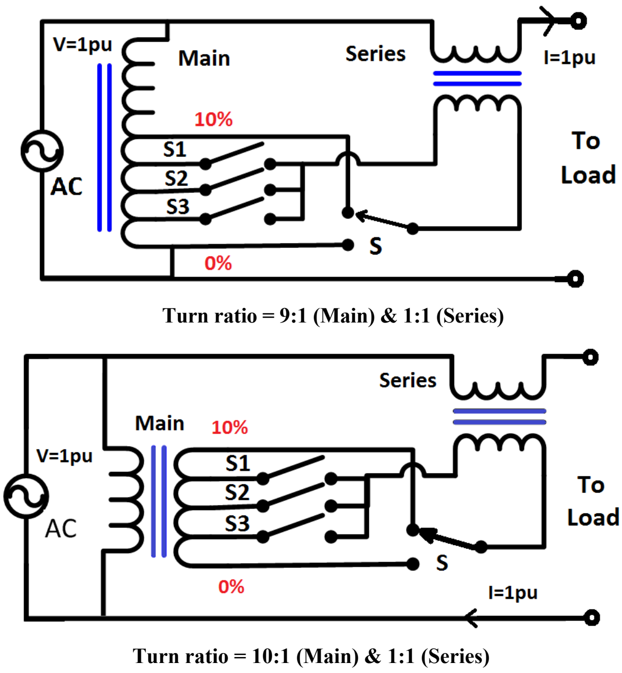


Fig. 8. Topology 5 and 5a developed based on topologies 4 and 4a using a selector switch to determine the sign of voltage compensation.

F. Topology 6 and 7

In an attempt to use a single transformer for compensation that is rated only for the compensating power of 0.1p.u., topology 6 and 7 are obtained. They use a step-down type center-tapped series transformer as shown in Fig. 9 and Fig. 10. The transformers have a turn ratio of 100:1 and 20:1 respectively. For topology 6, either the top set (S1, S2) or the bottom set (S3, S4) of switches are ON, providing negative and positive compensation respectively. If N_2 is the number of turns of the secondary, the taps for -10% (S2), -6% and -2% (S1) compensation are positioned at 10 N_2, 16.66 N_2 and 50 N_2 respectively so as to satisfy Eqn. (1). The tap switches have to be rated for blocking voltages between 6p.u.and -4p.u. depending on their position. This is explained as follows - when S2 is ON, as per Fig.9 (bottom) S1 will have 1p.u. voltage on its left side and 5p.u. voltage on its right side, thus blocking (1p.u.-5p.u.) = -4p.u. overvoltage across it. At the same time, S4 will have to block 1- (-5p.u.) = +6p.u. voltage across it. The worst case is when all the tap switches are OFF. The transformer boosts voltage from the secondary by the turn ratio of 100:1 and up to 51p.u. and -49 p.u. voltage is seen across the switches.

In topology 7 shown in Fig. 10, the taps are moved to the secondary side - the benefit being that the switch voltage ratings in OFF condition are reduced. The drawback of this design is that the tap switches directly carry the load current and are not isolated from the source or load. A selector switch determines the polarity of the compensation voltage. The series transformer primary and secondary are rated for 2p.u. and 0.1p.u. voltage respectively. To evaluate the ratings of the switches - when one tap is ON, say S1 providing 10% compensation, the other switches will have to block up to 0.1p.u. voltage. The selector switch has to block ±2 p.u.

voltage between the input and unconnected output terminal. The ratings of transformer and switches for both topologies are summarized in Table 1 and Table 2.

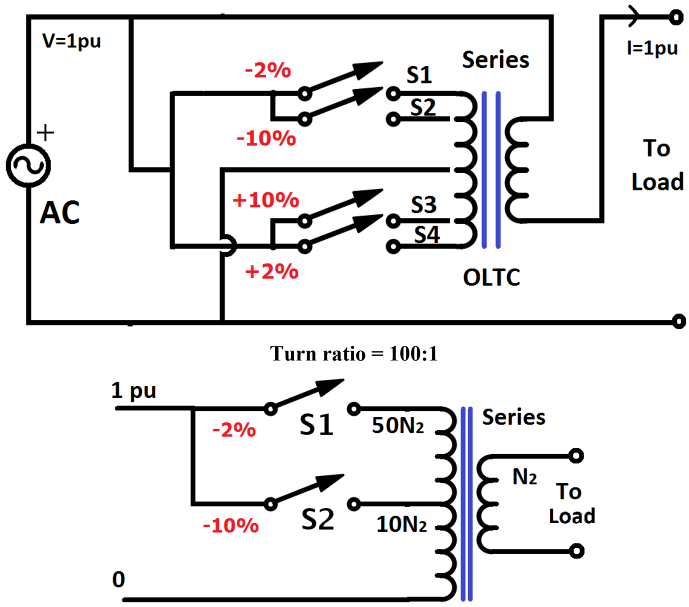
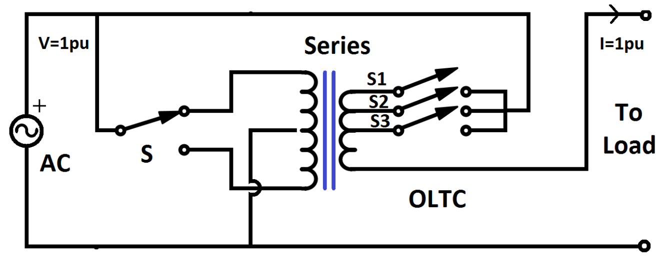


Fig. 9. Topology 6 (top) built using a single series transformer with taps. The upper windings of the primary side (bottom) provide negative compensation



Turn ratio = 20:1

Fig. 10. Topology 7 built using a single series transformer with taps

TABLE I. SUMMARY OF VOLTAGE, CURRENT AND POWER RATINGS OF TRANSFORMER FOR ALL OLTC TOPOLOGIES

Topo-logy	Rating of main transformer (p.u.)					Rating of series transformer (p.u.)				
	V		*I*		*S*	*V*		*I*		*S*
	1''	2''	1''	2''		1''	2''	1''	2''	
1	1	1.1	1.1	1	1.1	-	-	-	-	-
1a	1.22	1.1	1.1	1	1.1	-	-	-	-	-
2	1	0.2	1.1	1	1.1	0.1	0.1	1	1	0.1
3	1	0.1	0.1	1	0.1	-	-	-	-	-
3a	0.9	0.2	0.1	1	0.1	-	-	-	-	-
4	0.8	0.2	0.1	0.9	0.1	0.1	0.1	1	1	0.1
4a	1	0.2	0.1	1	0.1	0.1	0.1	1	1	0.1
5	0.9	0.1	0.1	0.9	0.1	0.1	0.1	1	1	0.1
5a	1	0.1	0.1	1	0.1	0.1	0.1	1	1	0.1
6	-	-	-	-	-	10	0.1	(0.1, 0.02)	1	0.1
7	-	-	-	-	-	2	0.1	0.1	1	0.1

TABLE II. SUMMARY OF VOLTAGE, CURRENT AND POWER RATINGS OF TRANSFORMER FOR ALL OLTC TOPOLOGIES

Topo-logy	No. of switches	Tap switch rating (p.u.)				Selector switch rating (p.u)	
		I	V_b *(One tap close)*		V_b *(All taps open)*	*I*	V_b
			Forward	*Reverse*			
1	10+1	1	(0.2, 0)	(0, 0.2)	(1.1, 0.9)	-	-
1a	10+1	1	(0, 0.2)	(0.2, 0)	1	-	-
2	10+1	1	(0.2, 0)	(0, 0.2)	(1.1, 0.9)	-	-
3	(5+1)+1	1	(0.1, 0)	(0, 0.1)	(1.1, 1)	1	-0.1, 0.1
3a	10+1	1	(0.2, 0)	(0, 0.2)	(1.1, 0.9)	-	-
4, 4a	10+1	1	(0.2, 0)	(0, 0.2)	(-0.9, -1.1)	-	-
5, 5a	(5+1)+1	1	(0.1, 0)	(0, 0.1)	(-1.1,-1)	1	-0.1, 0.1
6	10+1	(0.02, 0.1)	Upto 6	Upto 4	(-49, 51)	-	-
7	(5+1)+1	1	(0.1, 0.04)	(0.1, 0.04)	(-0.9, -1)	0.1	-2, 2

IV. CONCLUSION

Different topologies of solid-state OLTC that use both autotransformers and two-winding transformers have been compared on the basis of the voltage and current ratings of the transformer and power electronic tap switches. The eleven topologies are designed to provide both positive and negative compensation of the grid voltage.

For voltage control applications where isolation of source and load is required, topology 1, 1a and 2 that use a conventional two-winding transformer of 1.1p.u. power rating are most suitable. They can be implemented on sub-transmission transformers and distribution transformers in the network.

If source-load isolation is not required, using an autotransformer is more cost effective option offering a higher throughput power and copper savings. Topologies 3, 4 and 5 offer this advantage.

The topologies using *(N+1)* switches namely 3, 5, 5a and 7 have the benefit of needing lesser number of tap switches compared to topologies like 3a, 4, 4a and 7 that require *(2N+1)* switches. However the topologies with *(N+1)* switches also have two drawbacks. One is that they require an additional selector switch S whose design and ratings must be considered. Secondly the load current passes through two switches during steady state (selector and tap switch), leading to higher conduction losses. Thus based on the network voltage, power levels and a combination of the above three factors will determine which topology is most suitable for that application.

When topology 3 and 7 are compared, both require the same switch rating and number of switches. However topology 3 uses an autotransformer that has half the voltage rating as that in topology 7. So design 3 is preferred over 7.

Depending on the actual voltage, power levels and fault conditions of the network and type of semiconductor switch being used in the OLTC, Table 1 and Table 2 will be a useful tool to compare and choose the most suitable power electronic (assisted) OLTC topology for voltage regulation.

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