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Design and Control a High Gain Synchronous Buck Converter for a Solid State Distribution Transformer

Design and Control a High Gain Synchronous Buck Converter for a Solid State Distribution Transformer

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Abstract. A Conventional distribution transformer consists of bulky windings, cores and coolant liquid hence it is weighty and large in size. Now days, supporting by development of power semiconductor devices, the idea to develop distribution transformers using switching power converter technology becomes viable. This paper proposed a new structure of a solid state transformer (SST) for power electrical distribution system. The proposed SST works without utilizes high frequency isolating transformer. Instead, high gain cascaded Buck converters are used. The design of Buck Converters involves calculation of the applied components such as Inductors and Capacitors. Simulation result verifies that Buck Converters work well to reduce DC voltage of 25 kV DC voltage to 620 V DC without excessive ripple. The proposed SST is successfully operated to step down 20 KV of AC voltage to 400 V with THD of output voltage less than 2 %.

1. Introduction

Transformers take a very important role in power electrical system. Distribution (transmission) lines operate in high voltage system to reduce the current flow in the conductor hence reduces the voltage drop as well as power loses in the system. Transmission lines work at 500 kV or 150 kV and then stepped down to 20 kV in the distribution line. In the load side the 20 kV voltage is reduced to 220/380 V for the safety reason. Reliability of power electrical system is fully depended on the existence of transformers. Conventional transformers involve bulky winding, cores, and liquid as a coolant. As a consequent, the size of transformers is large, heavy and the lubricant waste causes bad effect to environment.

Recently, supporting by a rapid development in the solid state technology, conventional distribution transformers have been proposed to be replaced by power electronics devices that leads to solid state transformer (SST). Unlike conventional transformers that work based on electromagnetic induction principle, SST operates based on switching power electronic converter technology. Advantages of SST over conventional transformer are compact in size, significant reduction in weight, environmentally friendly and flexibility in power factor control using closed loop control [1,2]. SST has been successfully applied in many applications namely Railway Tractions, Smart Grid, Power Quality Improvement[3-5]. Recently, SST is also applied in Power Distribution System. [6-8]

The first structure of SS-trafo has been initiated in 1980 by Navi Researchers [9]. The structure was then improved by EPRI Corp..in 1995 [10]. The common topology of SST consists of power electronic converter and high frequency transformer as is shown in Figure 1. In high frequency operation, the size of conductors is significantly reduced hence reduce the dimension of the transformer. It is clearly shown in Figure 1 that, operation of SST involves of three main stages i.e rectification stage that converts high AC voltage to high DC voltage, DC to DC stage that converts high voltage DC to low voltage DC and inverter stage that converts the low DC voltage into low AC voltage in the load side. In particular, the DC to DC stage involves DC to AC part (Inverter), high frequency transformer and AC to DC part (rectifier).[11,12] One drawback of the SST with high frequency transformer is that the efficiency system can be reduced since a high frequency operation increases transformer losses especially core losses and conductor skin effect.

In order to solve the problem, a new structure of SST is proposed. The proposed SST replaces the high frequency transformer with cascaded DC to DC converter as shown in Figure 2. This paper proposed design and control of cascaded high gain Buck Converters for a power distribution system. The design is emphasized in the calculation of the involved components in the Buck Converters, as well as controlling Buck Converters to step down the DC voltage of 20 kV into 600 V. The proposed SST is designed to convert a AC voltage input of 20 kV to 220/400 V in the secondary side with acceptable voltage quality (THD less than 5%).

2. Design of Solid State Transformer

It has been mentioned in the previous section that the proposed SS transformer utilizes high gain DC to DC Converters instead of uses a high frequency transformer as shown in the Figure 2. Here, the DC to DC converter operates to step down a 25 kV DC voltage to 600 V DC voltage. Subsequently, a 600 V DC is used as an input for a three-phase inverter to achieve a 400 V line to line voltage or 220 V phase to neutral voltage

A common Buck Converter applied one power switch and one diode. In high voltage and high current operation, it is preferable to replace the diode with a power switch that leads to a Synchronous Buck Converter. Using Synchronous Buck Converter is advantageous because the efficiency is improved and higher power rating [13]. The two switches operate in complementary manner hence two pulse signals with opposite pattern are required to control the two switches. In order to achieve high power gain of DC to DC converter, three Buck Converters are arranged in series connection or known as cascaded Buck Converter as is shown in Figure 3. Cascaded structure has been applied in some application for Boost Converter as presented in the literatures [14]

Output voltage of Buck Converter is governed by dyty cycle according to equation (1) In order to achieve output with acceptable ripple, the value of Inductor and Capasitor have to be calculated using equations (2) and (3). [15]. In this design, the Buck Converters are controled by using MOSFET with frequency switching of 20 k Hz, duty cyce of 20% for the all Buck Converters, expected ripple less than 5% the minimum value of Inductors (L) and Capacitors (C) are 2.5 e^{-3} H and 8 e^{-6} F respectively.

$$V_{dc} = DV_{in} \quad (1)$$

$$L_{min} = \frac{(1-D_{min})R\max}{2.f_s} \quad (2)$$

$$C_{min} = \frac{(1-D_{min})R\max}{8L.f^2{}_s(\frac{\Delta vo}{V_s})} \quad (3)$$

where, D is duty cycle, f_s is frequency switching of power switches, R is resistance load and $\Delta v_0/Vs$ is the desired ripple of the output voltage

3. Results and Discussion

The proposed SST is verifieed using Simulink Matlab. The power semiconductor swithes are modelled using Sim PowerBlockSet. Buck Converters utilize IGBTs and Inverter uses MOSFETs. The complete parameter of Buck Converters including the specification of IGBT is presented in Table 1.

The proposed SST utilises 6 switches full wave rectifier to achieve full wave rectification. In simulation, Rectifier utilizes Thyristors instead of Diodes in order to achieve higher power rating of component. Input output waveforms of rectifier are shown in Figure 4. It is depicted that rectifier converts 20 kV line to line rms voltage to 25,3 kV DC voltage. The result is match with expectation since in a full wave rectification. Further, the performance of Buck Converter is discussed. DC to DC converter takes a very important role to achieve high range of DC voltage conversion i.e reduce the 23 kV DC voltage to 600 V. The DC to DC conversion operates simultaneously in three steps as presented in Figure 4.

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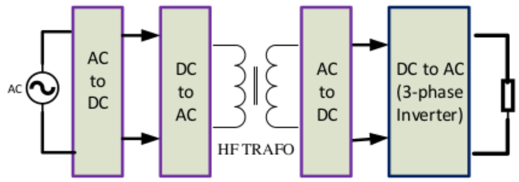


Figure. 1. Common topology of SST.

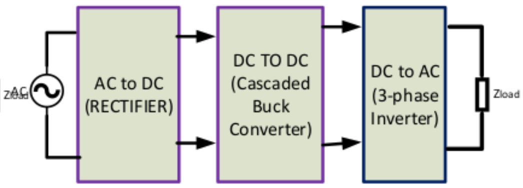


Figure 2. Proposed Solid State Transformer

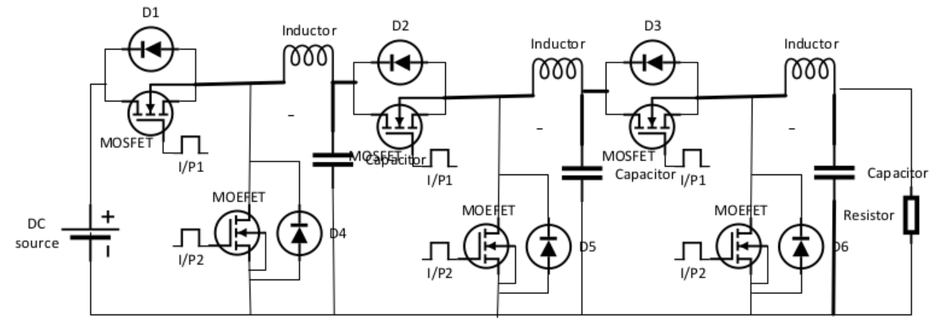


Figure 3. Cascaded Asynchronous Buck Converter Circuit

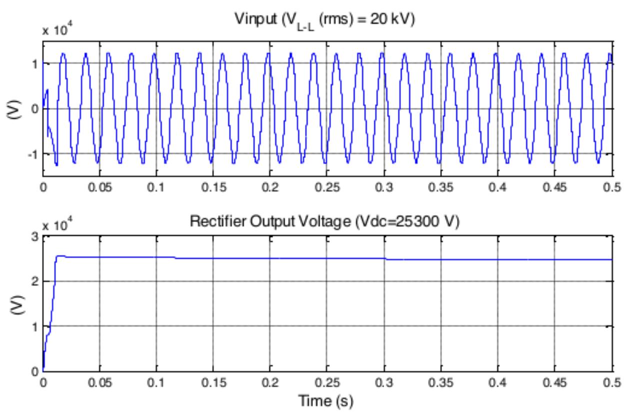


Figure 4. Rectifier input – output voltage waveforms

Table 1. Parameter simulation of DC to DC converter

Component	**Symbol**	**Value**
Switches	IGBT	
Snuber resistance	R_s	1e5 Ohm
Resistance	R_{on}	0.01 Ohm
Inductor	L	2.5 e-3 H
Capacitor	C	8 e-6 F
Frek. switching	Fs	20.000 Hz
Duty Cycle	D	20%

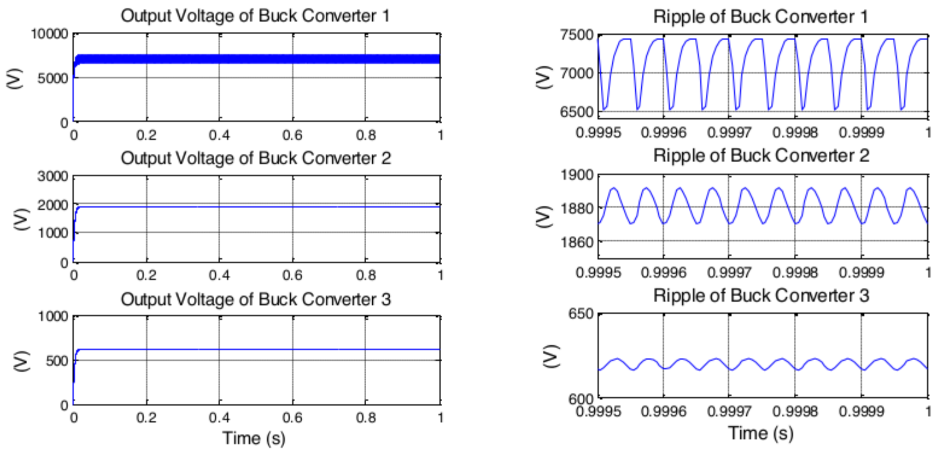


Figure. 5. Output voltage of Buck Converters (a) and the respective ripple (b)

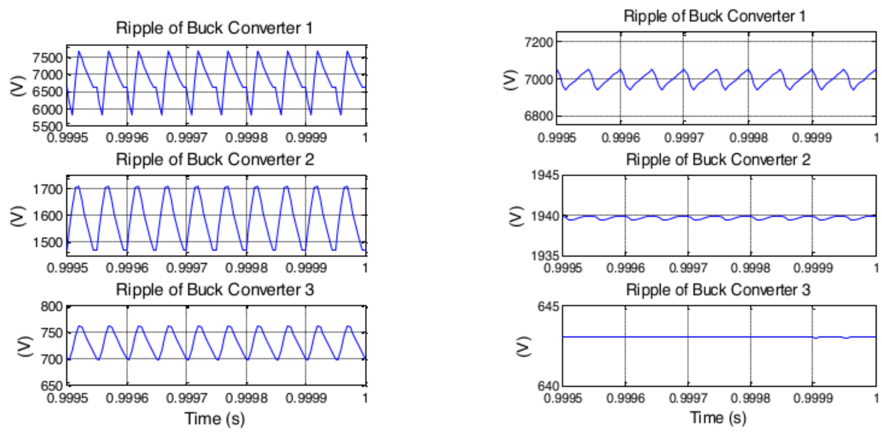
It is revealed in Figure 5 that gradual reduction of DC voltage is achieved from 23 kV to 8.000 V and then subsequently 8000 V reduces to 1900 V and finally, 1900 V reduces to target DC voltage of 600 V. The DC output voltages are matches with expectation since Buck Converters operate using 20% duty cycle (d). The final DC output 600 V DC voltage contains less than 5% ripple with respect of the target voltage as shown in Figure 5 (b). This result indicates that selection of used components (*L* and *C*) has been properly designed. Improper values of *L* and *C* causes excessive ripples that potentially causes distorted SST output voltage. Figure 6 shows the DC voltage output ripple for various values of L and C. Giving L and C lower than the designed value causes significant ripple in the output (Figure 5a). On the other hand, giving the higher values of L and C, it may reduce the ripple but effect to the cost and availability of the component in market (Figure 5b).

The 600 V DC voltage is then use as an input of inverter. The three phase inverter utilizes six IGBT power switches. The switches are controlled using sinusoidal PWM technique with frequency switching of 2 kHz to achieve 400 V rms line to line output voltage. Figure 7 shows the unfiltered and filtered line-to line output voltage waveform of inverter and the harmonics spectra. It is clear that the unfiltered voltage contains free low-order harmonics. The low-order harmonics are shifted into around multiple switching frequency and its side band. Moreover, Figure 7 (b) depicts that sinusoidal output voltage has been achieved by applying a proper filter. It is witnessed in the spectrum that fundamental component of output voltage contains of about 400 V (rms) line-to line voltage. Voltage waveform is free from harmonics content hence THD reduce from 68.8% to 1.081%.

Finally, the whole input-output voltage waveform of the proposed SST is presented in Figure 8. It is clearly shown that the 20 kV AC voltage has been successfully step down into 420 V of output voltage with THD less than 2 %. This result indicates that the distribution transformer can be realized using switching power conversion concept without using any windings transformer that works using voltage induction principle. It is however, the only drawback of SST is that the load current can be badly distorted due to the applied power semiconductor devices with high switching frequency..

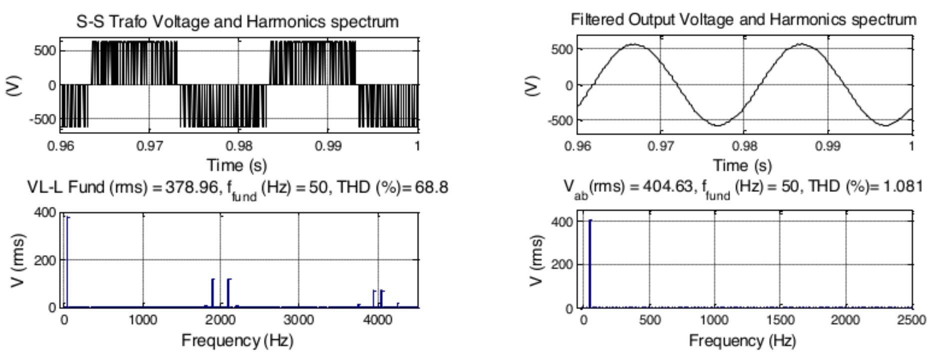
4. Conclusion

This paper proposed a new solid state distribution transformer. Instead of using high frequency transformer, high gain of Buck Converters is applied. In order to achieve of high range of voltage reduction, three Buck converters are operated in cascaded. The proposed SST is verified using Matlab/Simulink. Simulation result shows that the cascaded Buck Converters work well to reduce 25 kV DC into 620 V DC with DC voltage ripple less than 5 %. It is also shown that the inverter part also shows a good performance to reach the expected voltage output of 400 V with THD less than 1.5%.



(a) (b)

Figure 6. Output voltage ripple of Buck Converters for various values of Inductor and Capacitor



(a) (b)

Figure 7. Unfiltered (a)and filtered inverter's output voltage (b)

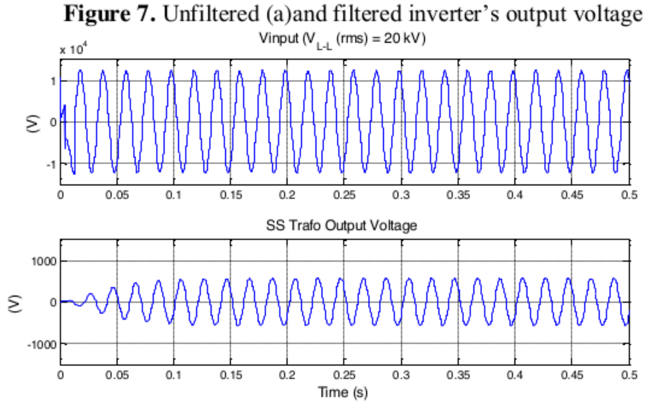


Figure 8. Input and final output of the proposed SS Transformer

In general, it is proven that the proposed SST has been successfully developed to convert a 20 kV AC voltage to 400 V rms line to line voltage. The only thing that needs to be further considered in realizing the proposed SST is that the highly distorted load current may happen due to the use of high frequency switching of power semiconductor devices.

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