Trapezoid Current Modulated DCM AC/DC DAB Converter for Two-Stage Solid State Transformer

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Abstract

Solid state transformer topologies (SST) have gained great attention because of having features such as reactive power compensation, output voltage regulation and smart grid operation etc. Among SST topologies, three-stage topologies have been mainly focused because there are many appropriate topologies for each conversion stages. However, conventional three-stage topologies may bring complex closed loop control methodologies, high value inductances and capacitances and hard switching losses. In this study, we proposed trapezoid current modulated DCM AC/DC DAB converter for two-stage SST. The proposed converter achieves soft switching; hence it can have high efficiency. Moreover, it can be operated by open loop control with eliminating high-frequency current sensors. In this paper, the analysis of the proposed converter is presented and theoretical analyses are validated by simulations.

1. Introduction

Due to the advantages of providing isolation and changing the voltage level in cheap way, the line frequency (50/60 Hz) transformers (LFT) are the main parts of the electrical power transmission and distribution systems [1]. However, LFT's have disadvantages such as output voltage sag during the input voltage drop, unable to correct power factor, incapable of storing energy due to lack of a DC bus, possible leakage of cooling oil to environment, etc. [2]. Moreover, LFT's have high volume and weight problems which are resulted from heavy cores and windings [3].

Since the line frequency is constant, decreasing the volume and weight can be only possible with saturation flux density. However, the development and commercialization process of high-flux-density materials are very slow, and this is the major obstacle to the reduction of the size and weight of LFT's.

Due to aforementioned disadvantages, the Solid State Transformer (SST) topologies have been investigated recently [4]–[16]. In [10], SST topologies were classified in three group as single, two and three stages. Although, single-stage topologies have simple control and high efficiency advantages, they don't include a DC bus [5], [11], [12]. Hence reactive power compensation can't be accomplished. On the other hand, since two-stage topologies have to convert High Voltage AC (HVAC) to Low voltage DC (LVDC) in a single stage, they hardly ensure soft switching [10]. In the literature, there are many appropriate topologies for each conversion stages of three-stage SST topology. Hence, three-stage SST topologies have been mostly studied [6]–[8], [13], [15]–[17].

Most of the three-stage SST topologies include Cascaded H-Bridge (CHB) rectifier, phase shifted DC/DC Dual Active Bridge (DAB) converter and back-end inverter [2], [13], [16]. Since CHB converter operates under the hard switching condition, the switching frequency has to be chosen low (nearly 10 kHz) for keeping the conversion efficiency high. However, this situation brings distortion in the input current because of the low bandwidth of the controller [18]. Additionally, the input inductance of the CHB rectifier must be chosen high in order to obtain low THD [2], [13], and this increases the size of the inductance. On the other hand, phase shifted DC/DC DAB converter suffers from hard switching [19], [20]. On the other hand, since the phase shifted DAB converter operates under the Continuous Conduction Mode (CCM), expensive high frequency current sensors must be used [21]. Expensive high frequency current sensors can be eliminated by Discontinuous Conduction Mode (DCM) operation [22], [23].

DAB converter can be operated under the DCM operation with triangular and trapezoid current modulation techniques [24]. Between these techniques, trapezoid modulation is more efficient at high loads [25]. In this paper, trapezoid current modulated DCM DAB AC/DC converter for two-stage SST is proposed and this converter is simulated with the PSIM simulation software. Simulation studies showed that, the proposed converter requires low filter inductance value which can help decreasing the volume of SST. Additionally, it eliminates high-frequency current sensors due to operation under open loop control.

2. Operation of the Proposed Converter

The peak inverse voltage (PIV) of switches can be reduced by the help of series cell configuration. Since, cells are operating with the same switching patterns (120° phase difference between cells); only one of the cell's operation is described in this section.

The proposed converter can be seen in Figure 1. By the help of synchronous rectifier, the input AC voltage is rectified. Then, output DC bus is obtained with trapezoid current modulated DCM DAB converter. In half of the switching period, there are four operating modes which are given in Figure 2.

[t0-t1] Mode 1: Before the time *t0*, the current of the L_k inductance reaches zero because of DCM operation. When S1d, S4d and S6d are turned on, V_{dc1} voltage applied on the L_k and current starts flowing from zero. The current of the leakage inductance can be written as:

$$I_{lk}(t) = \frac{V_{peak.} \, |\sin \omega t\,|}{L_k} t \quad , \quad t_0 \le t \le t_1 \qquad (1)$$

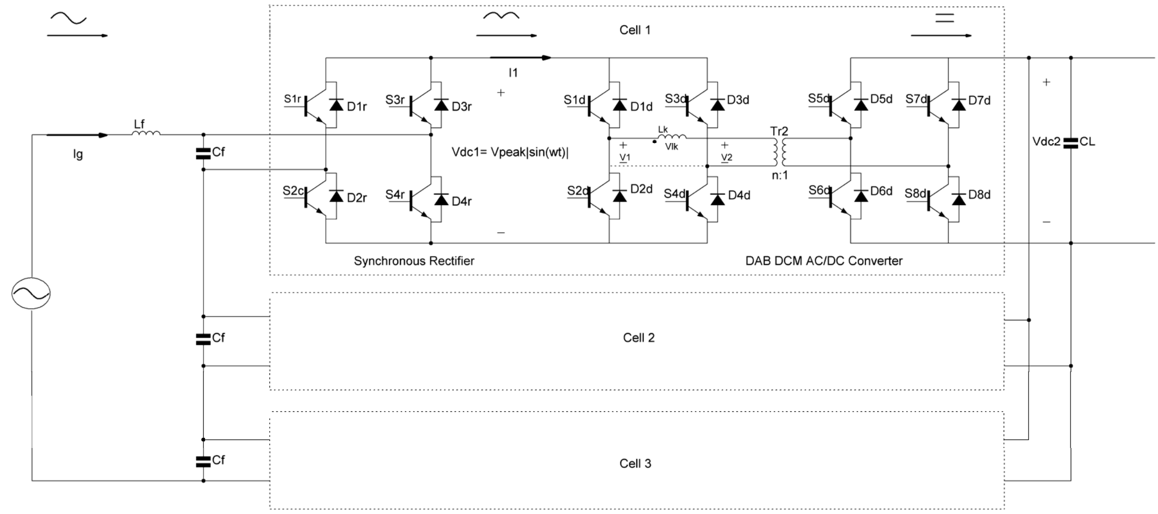


Fig. 1. The proposed trapezoid current modulated DCM AC/DC DAB converter

For the instant t_1, $I_{lk}(t_1)$ can be calculated with (2),

$$I_{lk}(t_1) = \frac{V_{peak.}\,|\sin \omega t\,|}{L_k} t_{on1} \qquad (2)$$

Where t_{on1} is the duration of Mode 1 ($t1$-$t0$).

[t1-t2] Mode 2: In this mode, output (V_{dc2}) starts delivering energy. For this purpose, S6d is turned off under zero voltage switching condition by the help of internal capacitances of switches.

The current of leakage inductance can be written as follows:

$$I_{lk}(t) = I_{lk}(t_1) + \frac{V_{peak.}\,|\sin \omega t\,| - nV_{dc2}}{L_k}(t - t_1), t_1 \le t \le t_2 \qquad (3)$$

The current at the instant t_2 can be expressed as:

$$I_{lk}(t_2) = \frac{V_{peak.}\,|\sin \omega t\,|\,(t_{on1} + t_{on2})}{L_k} - \frac{nV_{dc2}}{L_k} t_{on2} \qquad (4)$$

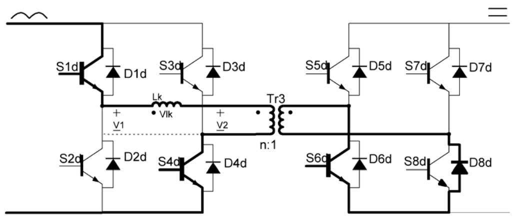
where t_{on2} is the duration of Mode 2 (t_2-t_1).

[t2-t3] Mode 3: In this mode, S1d is turned off, and all of the leakage inductance energy transferred to V_{dc2} until the current of L_k reaches zero. Leakage inductance current for this mode can be expressed as:

$$I_{lk}(t) = I_{lk}(t_2) - \frac{nV_{dc2}}{L_k}(t - t_2)\ ,\ t_2 \le t \le t_3 \qquad (5)$$

[t3-t4] Mode 4: In this mode, currents of switches and leakage inductance reach to zero. Hence, zero current switching condition can be ensured in Mode 1.

For utilizing the other half of the magnetizing curve of transformer, leakage inductance current is reversed by S2d and S3d in the other half of switching period [26].



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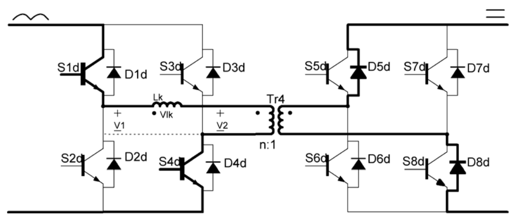

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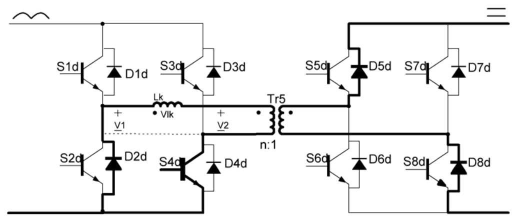

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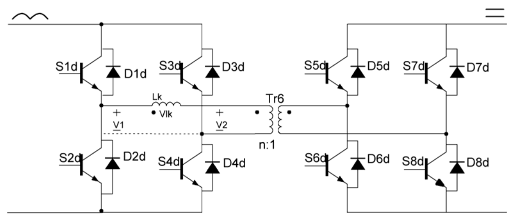


(d)

Fig. 2. Operating modes (a) Mode 1 (t0<t<t1), (b) Mode 2 (t1<t<t2), (c) Mode 3 (t2<t<t3) (d) Mode 4 (t3<t<t4)

3. Analysis of DCM Operation

The currents of L_k inductance and $I1$ (seen in Figure 1) are illustrated in Figure 3. In order to obtain purely sinusoidal grid current Ig (after filtering with L_f and C_f), the switching average of $I1$ must be sinusoidal. The average of I1 can be calculated as:

$$I_{1,avg} = \frac{I_{lk}(t_1)(t_{on1}+t_{on2}) + I_{lk}(t_2)(t_{on2})}{T_s} \quad (6)$$

$I_{1,avg}$ must be in form:

$$I_{1,avg} = A\,|\sin \omega t\,| \quad (7)$$

In order to ensure (7), t_{on1} and t_{on2} must be modulated as:

$$t_{on1} = \frac{DT_s}{2} - \frac{DCT_s}{2}\sqrt{|\sin \omega t\,|} \quad (8)$$

$$t_{on2} = \frac{DCT_s}{2}\sqrt{|\sin \omega t\,|} \quad (9)$$

In these equations, D and C are constants. D represents duty ratio and C is a real constant between 0 and 1. In this study, converted power adjusted with D, while C is kept constant during all of the operation of converter.

In order to work under DCM operation, duration of $t_{on1}+ t_{on2} + t_{on3}$ must be below than $T_s/2$, and t_{on3} can be given as follows.

$$t_{on3} = \frac{I_{lk}(t_2)}{nV_{dc2}} L_k \quad (10)$$

Using (4), (8), (9) and (10), (11) can be obtained for maximum duty ratio:

$$D_m \le \frac{1}{1 - C + \frac{V_{peak}}{nV_{dc2}}} \quad (11)$$

By the help of (2), (4) (6), (8) and (9), the switching average of $I1$ can be rewritten as:

$$I_{1,avg} = \left(\frac{V_{peak}D^2 - nV_{dc2}D^2C^2}{4L_k f_s}\right)|\sin \omega t\,| \quad (12)$$

Using (12) and V_{dc1} voltage (V_{peak} |sin ωt|), input average power can be expressed as:

$$P_{in,avg} = \left(\frac{V_{peak}{}^2 D^2 - nV_{dc2}V_{peak}D^2C^2}{8L_k f_s}\right) \quad (13)$$

The necessary leakage inductance value can be calculated with (13).

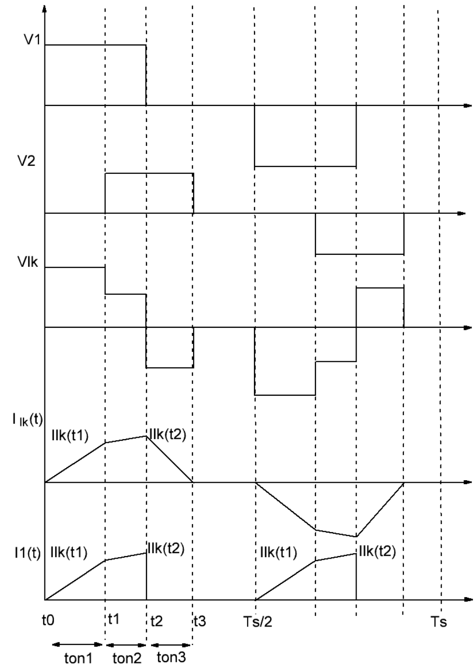


Fig. 3. The currents of L_k and $I1$

Table 1. Parameters of the Proposed Converter

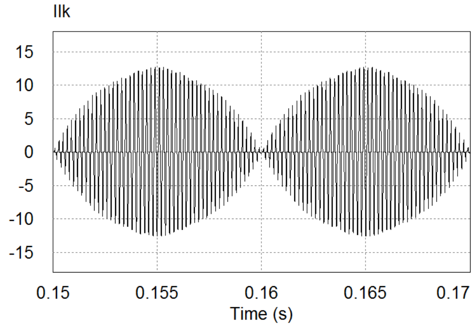
Parameter	Value
Turn ratio, n	1.5
Max. Duty, D_m	0.6
C	0.5
V_{peak}	2000 V
V_{dc2}	400 V
C_f, L_f	2 uF, 2 mH
C_l	2 mF
L_k	1.5 mH
Number of Series Cell	3
Max. $P_{in,avg}$	6.4 kW

4. Simulation Results

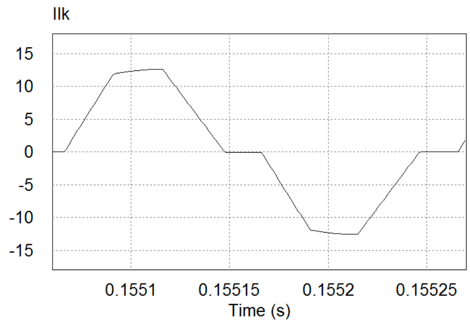
The simulations of the proposed converter were performed with PSIM simulation software. Three series cell configuration (seen in Figure 1) was used during simulations. The design parameters and the component values of the converter are listed in Table I.

The current of the L_k inductance is given in Fig. 4 for a grid and switching period. It can be easily seen from the Figure 4. b that the leakage inductance current has trapezoid wave shape and DCM operation is succeeded.

V_{dc1} and V_{dc2} voltages are drawn in Figure 5. The input filter (C_f and L_f) was chosen for filtering the switching harmonics. The input grid current is shown in Fig. 6. The current have %2.8 THD value and power factor is 0.995. Since, the filter circuit is second degree filter (40db attenuation), V_{dc1} and I_g have small ripples. If the input filter of the proposed converter is compared with the input filter (20db attenuation) of conventional three-stage SST, it can be said that the proposed converter can reduce the value of input inductance.

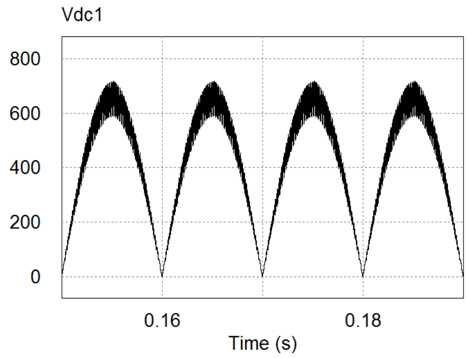


(a)



(b)

Fig. 4. The current of L_k for (a) a grid period and (b) switching period (D=0.5, C=0.5, $P_{in,avg}$=4.8 kW)



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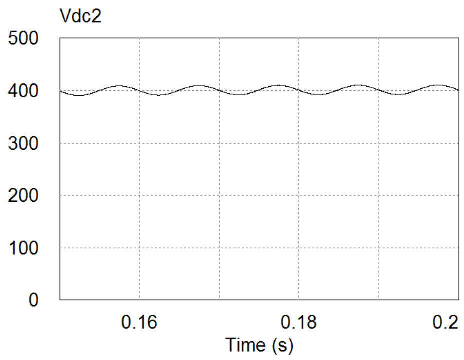

(b)

Fig. 5. (a)V_{dc1} and (b) V_{dc2} voltages (D=0.5, C=0.5, $P_{in,avg}$=4.8 kW)

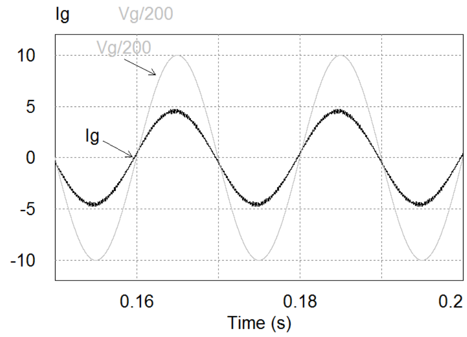

Fig. 6. Input voltage and current (D=0.5, C=0.5, $P_{in,avg}$=4.8 kW)

6. Conclusions

In this paper, a new topology for two-stage SST is proposed. In this topology, the sinusoidal input voltage is rectified by the help of synchronous rectifier, and sinusoidal input current is formed with the trapezoid current modulated DCM AC/DC DAB converter. The proposed converter reduces high frequency stages, and it can reduce inductance value of the input filter when compared with conventional three-stage SST. Additionally, the high frequency switching stage is designed as soft switched with the help of DCM operation. Hence, the proposed converter can have low switching losses; in turn it can have high efficiency. On the other hand, since the proposed converter operates with open loop control, it eliminates the high expensive frequency current sensors.

7. References

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