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TIME DOMAIN ANALYSIS OF REACTIVE AND OPTIMAL MODULATION FOR ISOLATED DUAL BRIDGE DC/DC CONVERTERS

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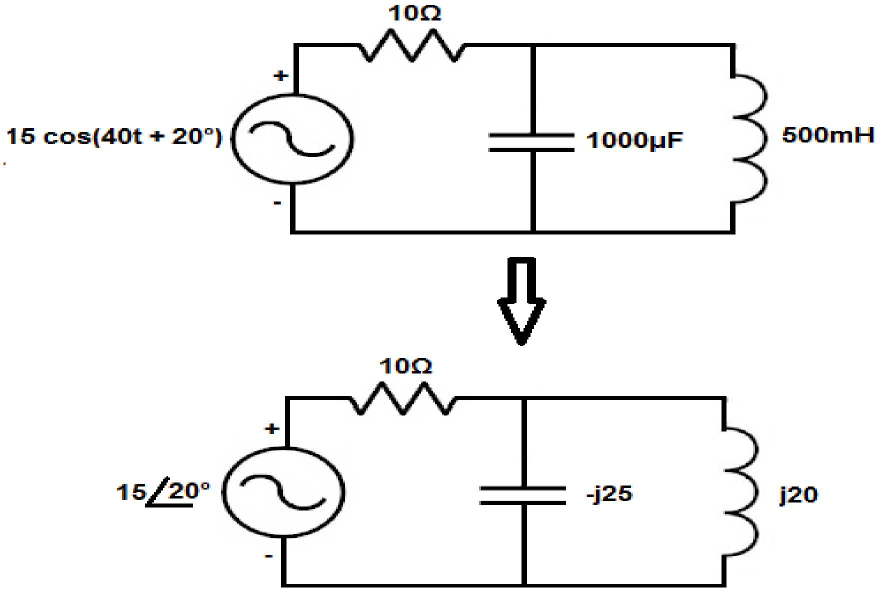
ABSTRACT

This letter discusses the reactive components and the power factor of dual-active-bridge converters under triple-phase-shift modulation. Different from previous methods based on backflow power integral or Fourier series expansion, this letter presents a straightforward analysis and categories of reactive current through time-domain analysis and then gives a unified time-domain definition of reactive current, reactive power, and power factor. Compared with all the previous definitions, the expressions of reactive components and power factors are much more concise and of profound physical meaning. On this basis, specific calculations of reactive power and power factor are derived for all practical voltage patterns and an optimal global power factor phase shift modulation is proposed to improve the power factor on both bridges. At last, the effectiveness of analysis and proposed modulation were validated using a 500-W laboratory prototype. The results showed efficiency improvements compared to other optimal power factor modulation strategies

1. INTRODUCTION

ISOLATED dual active bridge (DAB) converters are gaining more attention for the merits of simple structure, easy to control, and high power density. Single-phase-shift (SPS) modulation only utilizes the outer phase shift between high frequency (HF) voltages as control variable, and suffers huge HF current if the voltage gain is not matched with the high frequency transformer (HFT) turns ratio [1]. Numerous modulation strategies with more modulation parameters have been proposed in literatures to deal with this problem, such as extended-phase-shift(EPS) modulation in [2] and [3], dual-phase-shift (DPS) modulation in [4], and triple-phase-shift (TPS) modulation strategies for different optimization goals [5]–[8].In order to study and quantify the effect of different modulation strategies, many works focused on the reactive power or the power factor in the HF link. Concept of reactive power was originally pro-posed in [4]. Based on this definition, the reactive power equals the flow back power and is generated by the phase different between the HF voltage and the HF current on primary bridge. However, the physical significance is not clear as the HF components are non Sinusoidal . The current stress was used to indicate the reactive power in [8], which lacked direct linking. Authors in [9]–[11] defined the reactive power Centered)

Power Manuscript received January 7, 2019; revised January 20, 2019; accepted January 28, 2019. Date of publication February 1, 2019; date of current version May 22, 2019. This work was supported by the National Key R&D Program of China under Grant 2017YFB1200901-12. (Corresponding author: Zedong Zheng) The authors are with the Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail:,wse15@mails.tsinghua.edu.cn; zzd@tsinghua.edu.cn; lichi@tsinghua.edu.cn; wangkui@tsinghua.edu.cn; liyd@tsinghua.edu.cn).Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.Digital Object Identifier 10.1109/TPEL.2019.2897007Fig



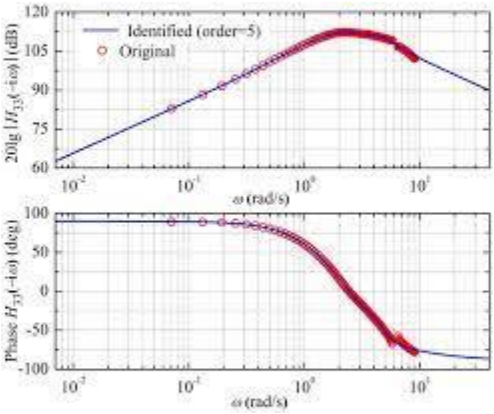
and the power factor based on Fourier series expansion. The reactive power was generated by all the HF components and was express din form of infinite series, whose summation was hard to be derived. So [9] and [10] only came up with modulation strategies to minimize the fundamental reactive power of the primary bridge. Besides, the se modulation strategies turned out to be special cases of EPS modulation and failed to cover the whole power range. Further in [11], authors considered up to the seventh order harmonics and adopted particle swarm optimization to obtain an optimized TPS modulation strategies. Still the higher frequency components were neglected and the optimization procedure was complex. Therefore, previous researches were difficult for practical use in the modulation parameters optimization and failed to present the straightforward influences of modulation parameters on re active power and power factor. Moreover, the primary bridge and the secondary bridge are equally important in the power transfer, but previous studies only considered the reactive power of the primary bridge. To clearly address reactive current and reactive power in DAB converters under TPS modulation, this letter presents a time domain analysis of HF current to derive unified analytical expressions of reactive current, reactive power, and power factor. On this basis, an optimal TPS modulation scheme is proposed to improve the power factor on both bridges and increase converter efficiency.

TIME DOMAIN ANALYSIS OF REACTIVE COMPONENTSA. Operation Principle of DAB With TPS Modulation Scheme Fig. 1 shows the circuit configuration and the equivalent circuit of a DAB converter. The converter consists of two full-bridges connected through an HFT. Turns ratio of the HFT is n:1. L1and L2includethe leakage inductance of HFT and the additional inductance. The dc voltages of the primary bridge and the secondary bridge are U1and U2, respectively. The full bridges work at frequency fs, and their voltage e outputs are u AB and u CD. DAB can be equivalent to two square voltage sources connected through the equivalent inductance, where all the parameters are refer re d to the primary side.

Fig. 2 shows the steady-state operation waveforms of TPS modulation. Power transfers from primary bridge to secondary bridge and equals P. The inner phase shift of the primary bridge is D1,anduABis a square wave with duty cycle of (1 −D1)/2. Similarly, the inner phase shift of the secondary bridge is D2, and duty cycle of u CD is(1 −D2)/2. D1and D2are commonly limited within [0,1]. The outer phase shift between u AB and u CD is D0, and is generally limited within[−0.5, 0.5]. All the phase shift parameters have influences on the HF current iL and power transfer characteristics, but the magnitude and the current stress of iL can be reduced through appropriate combinations .The voltage gain M and root-mean-square value of HF components are defined as M=nU2U1,UAB =RMS (u AB)=U1█1−D1IL=RMS (iL),UCD =RMS

Time Domain Analysis of Reactive Current In Fig. 2, the instant power is negative between t1and t2or betweent6and t7,soil during this time interval was usually defined as the circling current and the power during this time interval was defined as the reactive power in [4] and [5]. However, this definition is narrow to depict the influence of voltage mismatch and phase shift modulation, so a new analysis of the reactive current is proposed. U AB keeps zero from t4to t6, and the primary bridge cannot provide any active power during this time interval. However, I Lis not always equal to zero from t4to t6. Thus, iL does not transfer any power from primary bridge but still causes conduction losses. So this part of I Lis defined as the freewheeling reactive current .u AB equals U1from t1to t4, and the primary bridge transfers power during this time interval. The average value of iL between t1and t4isIave1 =P(1 −D1)U1.(2)If I Lis ideally even and equals Iave1 between t1and t4, the converter can transfer the same amount of power with the minimum current stress and current rms value. The rest part of iL during this interval fluctuate zero and does not transfer active power but increases both conduction and switching losses. Thus, it is defined as the fluctuant reactive current. It is worth mentioning that the circling current is included in the fluctuant reactive current. (u CD)=U2█1−D2.

Based on analysis above, the ideal current for primary bridge should have the same shape as u AB , A sip 1shown in Fig. 2. Generally, ip1transfers the same amount of power as iL, but with the minimum RMS value and current stress, and is defined as the active part of iL. The expression of ip1and its RMS value areip1=PUAB2uAB ,Ip1=RMS(ip1)= PUAB.(3)The rest part of iL contains freewheeling reactive current and fluctuate reactive current, and is the overall reactive current of the primarybridgeiq1=iL−ip1,Iq1=RMS(iq1)=□I2L−I2p1.(4)ip1and iq1are orthogonal in the switching period1T ■ T0ip1iq1dt =1T ■ T0ip1(iL−ip1)dt=P(1 −D1)U12T ■ T0uABiLdt −I2p1=P2(1 −D1)U12−P2(1 −D1)U12=0.(5)Similar analysis can be done to obtain the active current and the reactive current of the secondary bridge with variables referred to the primary sideip2=PnU2CDuCD,Ip2=RMS(ip2)= Pn UCD(6)iq2=iL−ip2,Iq2=RMS(iq2)=□I2L−I2p2.(7)C. Definition of Reactive Power and Power Factor Since ip1and iq1are orthogonal, the reactive power, the apparent power, and the power factor of primary bridge areQ1=UAB •Iq1(8)S1=□P2+Q12=UAB •□I2p1+I2q1=UAB •IL(9)λ1=PS1=PUAB •IL.(10)Note that (8)–(10) are the same as the summations of infinite se-Ries from frequency domain analysis in [9]–[11] and accord with the definitions for non sinusoidal single-phase systems [12]. However, the physical meaning and expressions are much more straightforward with the concept of reactive current through time domain analysis. Similar analysis can be done to obtain the power factor of the secondary bridgeasλ2=PS2= Pn UCD •IL.(11)Since the primary bridge and the secondary bridge are equally important in the power transfer, the global power factor is defined to quantify the effectiveness of modulation strategiesλ12 =λ1λ2=P2nUABUCD I2L=P2nU1U2I2L█(1 −D1)(1−D2).(12)Authorized licensed use limited to: Tsinghua University. Downloaded on October 28, 2020 at 01:58:30 UTC from IEE Explore. Restrictions apply.



Experiment Results A prototype was built to verify the theoretical analysis. The equivalent inductance was 27.4 µH, the turns ratio of HFT was 1:1, and Fs was 40 kHz. The input dc voltage varied between 60–90 V, and the reference output voltage was set to 75 V. For the digital implementation of OGPF modulation, D1and D2withdifferent D0and M was pre-calculated and stored in a lookup table. The input dc voltage and the output dc voltage were sampled, and a PI regulator took the output error to obtain D0. Then linear intermodulation was used to derive D1and D2from the lookup table with output D0and instant M. Figs. 6 and 7 show the experimental waveforms of OGPF modulation. The inner phase shift of the high voltage bridge was larger to improve the power factor. Fig. 8 shows the measured efficiency of different modulation strategies. PDF modulation provided the highest efficiency.

2. CONCLUSION

with time-domain analysis, reactive current can be divided into freewheeling reactive current and fluent reactive current. With that, reactive power and power factor are defined in the time domain with found physical meaning, and their specific expressions are derived with a concise form. An optimal global power factor modulation strategy is proposed, which can provide the highest global power factor and cover the whole power range. This method can also be adopted for other isolated DC-DC converters to achieve high power factor power transfer

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The normalized IL and Pf or different voltage patterns are derived, WHERE ERMD is the remainder term and is different for each voltage pattern.

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