Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

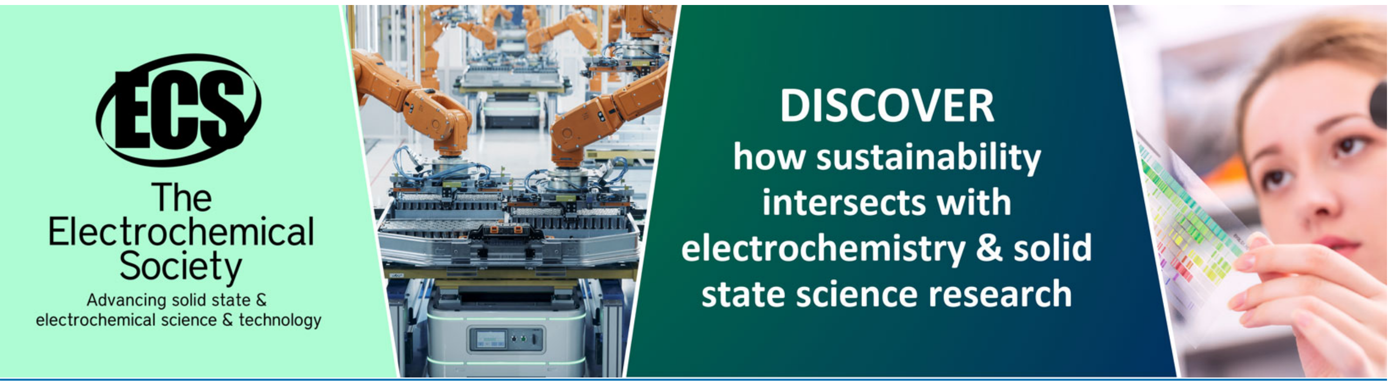
Current Stress Optimisation Strategy for Three-phase Dual Active Bridge Converter during the Start-Up Process

To cite this article: Guofu Chen *et al* 2020 *J. Phys.: Conf. Ser.* **1626** 012064

View the article online for updates and enhancements.

You may also like

- Enzymatic and catalytic behaviour of low-dimensional gold nanomaterials in modular nano-composite hydrogels
George Newham, Joseph Fox, Samuel C T Moorcroft et al.
- Full power range DAB unified ZVS control strategy based on low current RMS
Chuanqi Zhang, Fusheng Wang and Weizheng Cheng
- ReAsH/tetracystein-based correlative light-electron microscopy for HIV-1 imaging during the early stages of infection
Iryna Lysova, Coralie Spiegelhalter, Eleonore Réal et al.



This content was downloaded from IP address 18.218.145.131 on 17/05/2024 at 02:39

Current Stress Optimisation Strategy for Three-phase Dual Active Bridge Converter during the Start-Up Process

Guofu Chen[1,*], Xiaobin Mu[1], Xiang Wang[1], Honglin Jiao[2], Ruixiang Hao[2] and Wu Zhu[2]

[1]State Key Laboratory of Advanced Power Transmission Technology (Global Energy Interconnection Research Institute Co., Ltd.), Changping District, Beijing 102209, China
[2]School of Electrical Engineering, Beijing Jiaotong University, Haidian District, Beijing 100044, China

*Corresponding author email: chenguofu@geiri.sgcc.com.cn

Abstract. Three-phase dual active bridge (3p-DAB) converter is widely used in high-power bidirectional power transfer applications, due to its unique high power density and easy implementation of soft switching. In this paper, the start-up process of the 3p-DAB converter is studied. The cause of high current stress, especially in the case of heavy-load start-up is analysed, and a new start-up control strategy for the start-up process is proposed. The control strategy is helpful to reduce the current stress of the transformer and the switches by adjusting the duty-cycle and the phase shift angle coordinately without adding any other hardware circuits. Finally, based on a TMS320F28377D + XC6SLX25 controller, a 30kW 3p-DAB converter prototype with input voltage 650-750V and output voltage 400-500V is developed to verify the effectiveness of the proposed start-up strategy.

1. Introduction

With the increasing market demand for new energy power generation, energy storage system, and fast charging of electric vehicles, the DC distribution network system has been developed rapidly in recent years. As an essential part of it [1], the bidirectional DC-DC converter, such as single-phase dual active bridge (1p-DAB) converter has attracted considerable attention due to its many advantages, such as bidirectional power flow, galvanic isolation, and inherent soft-switching capability [2].

The three-phase dual active bridge (3p-DAB) converter is a variation of the 1p-DAB. It not only has the above advantages but also can achieve higher power transmission by using the three-phase interleaved structure. Besides, the 3p-DAB can reduce the size and weight of the filters and the transformer effectively to achieve higher power density [3].

In the traditional single-phase-shift (SPS) control of the DAB converter, the voltage of the capacitor at secondary DC side is zero at the initial state of start-up. So the leakage inductance is directly connected to the middle point of the primary H bridge, which causes a large current stress on the transformer and switches. As a result, higher current rating, expensive devices must be used in the converter to sustain the large current stress. Moreover, the inrush current in the high-frequency link makes electromagnetic interference (EMI) more serious, which may jeopardise the stable operation of the converter. Therefore, the soft-start method of DAB should be studied.

At present, the existing soft-start strategies for 1p-DAB are as follows: In [4], the pre-charging resistor is used during the start-up process, which can effectively suppress current spikes, but it requires

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

additional mechanical structures such as relays. In [5], the authors adopt the auxiliary circuit to realise soft-start, which also needs extra devices. The above two methods both increase the cost and complexity of the converter. A method of increasing the switching frequency during the start-up process is proposed [6], which can effectively reduce current stress. However, the variable frequency control brings more pressure to the driver circuits of the switches. Moreover, the frequency needs to be reduced to the normal operating value after the start-up process. This method may reduce the stability of the system. The secondary voltage is initially built up by the secondary side body diodes in [7]. This method can reduce the current stress effectively. However, oscillation may occur when the secondary side switches are turned on. In [8], the authors optimise the above methods and propose a closed-loop start method, in which the duty-cycle of primary bridge and the target voltage value ramp up synchronously. The relationship between the rising slope of duty-cycle and current stress during the start-up process is also analysed in detail [9]. It proves that the current stress can be reduced by adjusting the rising slope. However, this method is unsuitable for heavy load.

It is regret that there are few pieces of research on the 3p-DAB start-up process. The start-up control strategy with zero inductor current is proposed in [10], but it is realised on the premise that the voltage of secondary capacitor has already been established before the start-up. In [11], a space vector modulation method is proposed to enhance the power output capability under the condition of short-circuit or low voltage on the output side. However, the modulation method is so complicated that it is not convenient to be applied in the start-up process.

In this paper, the cause of the high current stress during the start-up process of 3p-DAB is analysed, and the relationship between the current stress and the phase shift angle is derived. A new start-up control strategy is proposed, which is verified by the simulation in PSIM. Finally, a 30kW 3p-DAB prototype is developed based on TMS320F28377D + XC6SLX25 to verify the effectiveness of the strategy proposed in this paper.

2. 3p-DAB Topology and Operational Principle

2.1. Circuit Topology

The topology of 3p-DAB is shown in figure 1. This circuit is mainly composed of three parts: inverter, high-frequency transformer, and rectifier. The upper and lower switches of each bridge leg of the rectifier and inverter units are in complementary conduction, and the three bridge legs operate alternately with 120° phase shift. The output voltage is controlled by the phase shift angle between primary and secondary bridges.

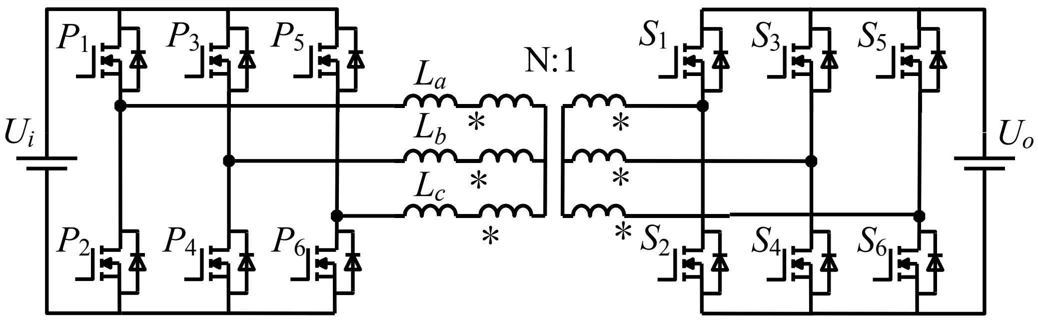


Figure 1. Topology of 3p-DAB.

2.2. Control Method

The typical waveform of the conventional single-phase-shift (SPS) modulation strategy is shown in figure 2. $S_{p1}S_{p3}S_{p5}$, $S_{s1}S_{s3}S_{s5}$ are the pulse of primary and secondary upper switches respectively; u_{p1} is the primary phase voltage of the transformer; u_{s1}' is the secondary phase voltage converted to the primary side; i_{s1} is the secondary side line current. This control method is quite simple. It only controls the phase shift angle ϕ between the corresponding bridge legs on both sides, and the full power range adjustment can be achieved through a single degree of freedom. The relationship between output power and phase shift angle is given by

$$P_o = \begin{cases} \frac{U_i U_o'}{\omega L}\phi(\frac{2}{3}-\frac{\phi}{2\pi}) & 0 \le \phi \le \frac{\pi}{3} \\ \frac{U_i U_o'}{\omega L}(\phi-\frac{\phi^2}{\pi}-\frac{\pi}{18}) & \frac{\pi}{3} \le \phi \le \frac{2\pi}{3} \end{cases} \tag{1}$$

Where $L = L_a = L_b = L_c$ is the three-phase equivalent inductance; $\omega = 2\pi f$, f is the switching frequency; U_i and U_o is the input and output voltage respectively; ϕ is the phase shift angle in radian.

3. Start-up Process Analysis

3.1. Analysis of Excessive Current Stress

The following is the analysis of the start-up process. In the first few cycles of the converter, the voltage of secondary DC side U_s is approximately zero. If the traditional SPS control is used to start, according to the single-phase equivalent circuit shown in figure 3, the phase voltage of the high-frequency link is a four-level stepped wave, as shown in figure 2, which will lead to current stress far beyond the normal working condition. This may cause damage to the switches. The current peak value is given by

$$I_{L\max} = \frac{\int_0^{\frac{T}{2}} u_{p1} dt}{L} = \frac{2U_i T}{9L} \tag{2}$$

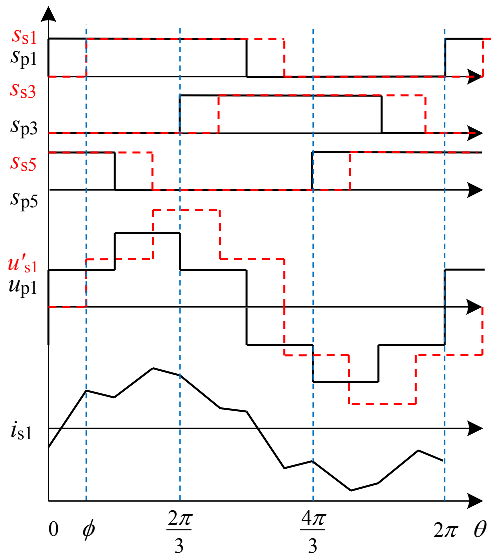


Figure 2. Waveforms under SPS control.

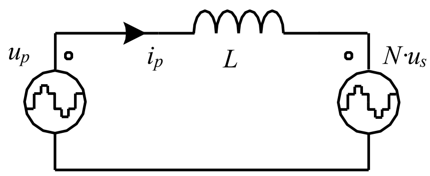


Figure 3. Single phase equivalent circuit of 3p-DAB.

Therefore, it is necessary to use the duty-cycle control method at start-up, so that the phase voltage of the primary and secondary sides of the transformer can be increased gradually. However, the problem of excessive current stress will occur during the duty-cycle control. As shown in figure 4, when the duty-cycle of both sides gradually increases to this state, the duty-cycle and phase shift angle meet

$$\begin{cases} D_1 = D_2 = 1/3 \\ \phi = 0 \end{cases} \tag{3}$$

Where D_1 is the duty-cycle of the primary upper switches, D_2 is the duty-cycle of the secondary upper switches, ϕ is the phase shift angle.

After the state shown in figure 4, the current value is only related to the secondary side voltage value and does not change with the increase of the duty-cycle. Therefore, when the phase shift angle is zero, the current stress reaches the maximum value at this state.

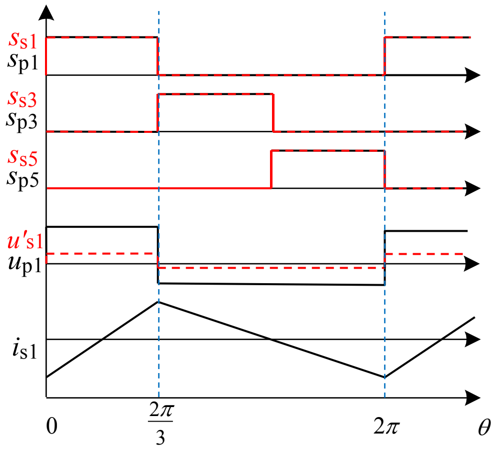


Figure 4. Waveforms of current stress maximum state.

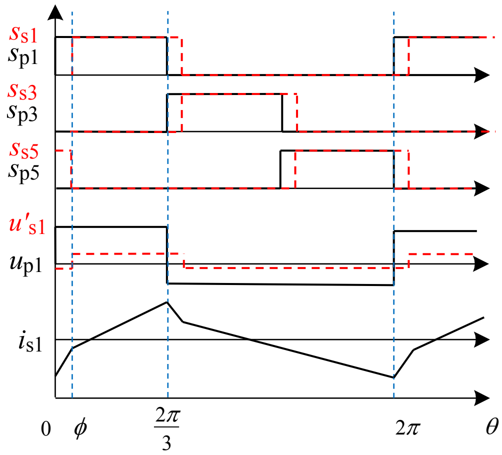


Figure 5. Waveforms of duty-cycle and phase-shift coordinated control.

3.2. Relationship between Current Stress and Phase Shift Angle

As shown in figure 5, assuming the initial inductor current value of the state θ=0 is i_0, and the time-domain analysis equations for one period are:

$$\begin{cases} i(\theta) = i_0 + \dfrac{2U_i + U_o^{'}}{3\omega L}\theta & 0 < \theta \le \phi \\ i(\theta) = i(\phi) + \dfrac{2U_i - 2U_o^{'}}{3\omega L}(\theta - \phi) & \phi < \theta \le \dfrac{2\pi}{3} \\ i(\theta) = i(\dfrac{2\pi}{3}) + \dfrac{-U_i - 2U_o^{'}}{3\omega L}\left(\theta - \dfrac{2\pi}{3}\right) & \dfrac{2\pi}{3} < \theta \le \dfrac{2\pi}{3} + \phi \\ i(\theta) = i(\dfrac{2\pi}{3} + \phi) + \dfrac{-U_i + U_o^{'}}{3\omega L}\left(\theta - \dfrac{2\pi}{3} - \phi\right) & \dfrac{2\pi}{3} + \phi < \theta \le 2\pi \end{cases} \tag{4}$$

T is the switching period, and ω satisfies

$$\omega = \frac{2\pi}{T} \tag{5}$$

According to the transformer inductance volt-second balance theorem

$$\int_0^{2\pi} \mathrm{i}(\theta) = 0 \tag{6}$$

Combining equation (4) and equation (6), the following expression can be obtained

$$i(0)=\frac{-2\pi U_i-(3\phi+2\pi)U_o}{9L\omega} \tag{7}$$

Because the secondary voltage is relatively low during start-up, it meets

$$U_i \geq U_{\mathrm{o}}^{'} \tag{8}$$

Therefore, the current stress reaches a maximum value at $\theta=2\pi/3$, maximum current is

$$i_{max}=\frac{2\pi U_i+(6\phi-2\pi)U_o^{'}}{9L\omega} \tag{9}$$

It can be seen that the current stress increases with the increase of ϕ, and decreases with the increase of U_o. Due to its three-phase interleaved structure, the input current fluctuation period is 1/3 of the switching period. The state interval of $(0,2\pi/3)$ is selected for analysis

$$I_{in}=\frac{\int_0^{\phi} i(\theta)\mathrm{d}\theta+\int_{\phi}^{\frac{2\pi}{3}} i(\theta)\mathrm{d}\theta}{2\pi/3}=\frac{(8\pi-9\phi)\phi U_i U_o^{'}}{12\pi L\omega} \tag{10}$$

Input power and output power are equal without considering the power loss, which is

$$P_{out}=P_{in}=I_{in}U_i \tag{11}$$

Assuming $R^{'}$ is the load resistance R converted to the primary side, then P_{out} satisfies

$$P_{out}=\frac{U_o^{2}}{R}=\frac{U_o^{'2}}{R^{'}} \tag{12}$$

Combine equation (10) – (12), U_o can be obtained

$$U_o=\frac{R^{'}(8\pi-9\phi)\phi U_i}{12\pi L\omega} \tag{13}$$

Bring equation (13) into equation (9), the relationship between the current stress and ϕ is given in equation (14).

$$i_{max}=\frac{U_i\left(\pi^2(12L\omega-8R^{'}\phi)-27R^{'}\phi^3+33\pi R^{'}\phi^2\right)}{54\pi L^2\omega^2} \tag{14}$$

From equation (14), it can be seen that increasing the phase shift angle can effectively reduce the current stress during start-up process.

4. The New Start-up Strategy

The start-up strategy with the coordinated action of duty-cycle and phase shift angle is proposed in this paper. The start-up process is shown in figure 6, and the implementation process is as follows:

(1) The duty-cycle of the primary and secondary sides rises according to the given ramp function, and the phase shift angle is calculated in real-time according to the secondary side voltage U_o and the voltage reference value U_{set}.

(2) If the duty-cycle is increased to 0.5, but the output voltage has not reached U_{set}, the converter enters the phase shift start-up stage. The phase shift angle will also rise with a given rate based on the current phase shift angle value.

(3) After the output voltage reaches U_{set}, the converter completes the start-up process and enters the closed loop stage. The duty-cycle and the phase shift angle of this moment will be the initial value of the closed-loop stage to avoid the oscillation caused by the sudden change of the parameters.

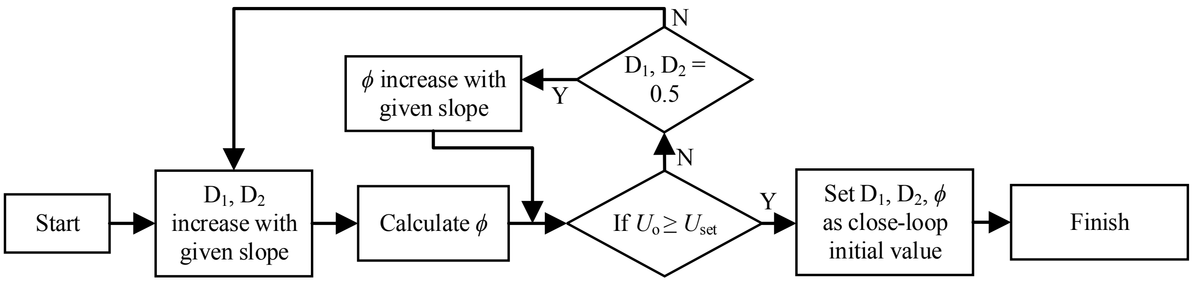


Figure 6. Flow chart of novel start-up strategy.

This start-up method has the following advantages: Firstly, the voltage gain is increased by the phase shift angle between the primary and secondary sides during the start-up process, which can reduce current stress. Secondly, at the beginning of the phase shift start-up stage, the phase shift angle can be increased based on a non-zero value, which can be calculated by equation (15), thus shortening the start-up process. Finally, when the converter is in light-load or no-load condition, the phase shift angle will decrease to zero as the voltage increases rapidly, which will not cause excessive gain problems.

In order to reduce the complexity of the start-up process and increase the compensation effect when the output voltage is low, a quadratic function is used in this paper to calculate the phase shift angle:

$$\phi = \mathrm{k}[1-(\frac{U_o}{U_{ref}})^2] \tag{15}$$

Because the range of the phase shift angle in the 3p-DAB is generally $(0,\pi/2)$, the value range of k is also $(0,\pi/2)$. In this paper, we choose $k=0.3$ to carry out simulation verification.

The start-up process of 650V input voltage, 500V output voltage, and load resistance 8.3 Ω is simulated by PSIM. Comparing the results shown in figure 7 and figure 8, it can be seen that the current stress is significantly reduced from 150A to 110A by using the novel start-up strategy.

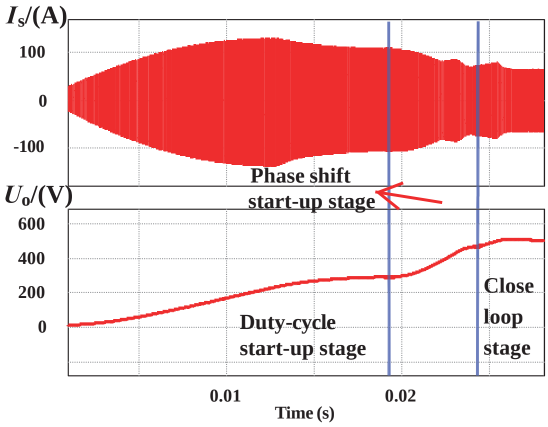


Figure 7. Simulation waveforms of duty-cycle start-up method.

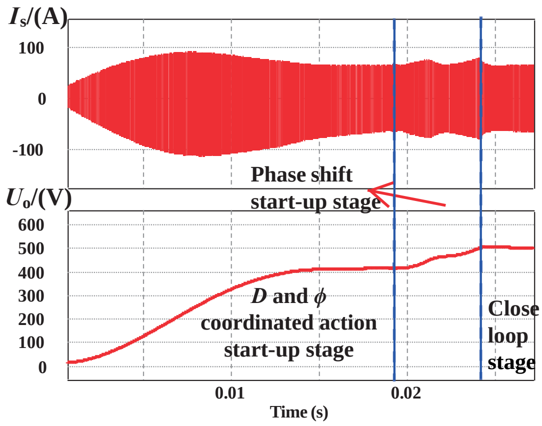


Figure 8. Simulation waveforms of the novel start-up strategy.

5. Experimental Verification

In order to verify the effectiveness of the start-up process optimisation strategy proposed in this paper, a 30kW experimental prototype with 650-750V input voltage, 300-500V output voltage is developed, which is shown in figure 9. CREE's SiC MOSFET half-bridge module CAS300M17BM2 and CAS300M12BM2 are used as the switches in high voltage side and low voltage side respectively; PT62SCMD17 and PT62SCMD12 are used as the gate driver of the switches. Nanocrystalline soft magnetic material is used as the core of high frequency transformer. TMS320F28377D DSP + XC6SLX25 FPGA are used as the controller of the converter. Parameters of the main circuit are shown in Table 1.

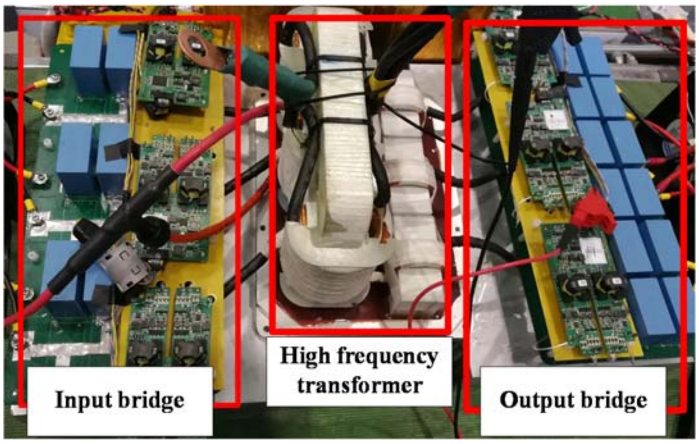


Figure 9. Main circuit of prototype.

In order to compare the current stress between the two methods, the same starting ramp function is used in the experiment. The waveform shown in figure 10 and figure 11 is carried out with input voltage 650V, output voltage 500V and 25 Ω load. It can be seen that the novel start-up strategy proposed in this paper can effectively reduce the current stress. Additionally, the output voltage has a faster rising slope during the initial stage of start-up. Moreover, there is no apparent oscillation and overshoot during the switching process of different start-up stages.

Table 1. Main circuit parameters.

Main Circuit Parameters	Value
Input voltage U_i /V	650-750
Output voltage U_o /V	400-500
Switching frequency f /Hz	50k
Transformer ratio r	1: 0.8
Leakage inductance $L/\mu\text{H}$	8
Primary side capacitor $C_i/\mu\text{F}$	180
Secondary side capacitor $C_o/\mu\text{F}$	360
Load resistance R/Ω	8.3

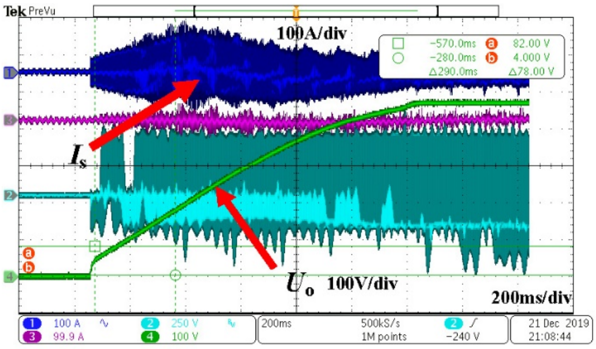


Figure 10. Experiment waveforms with duty-cycle start-up method.

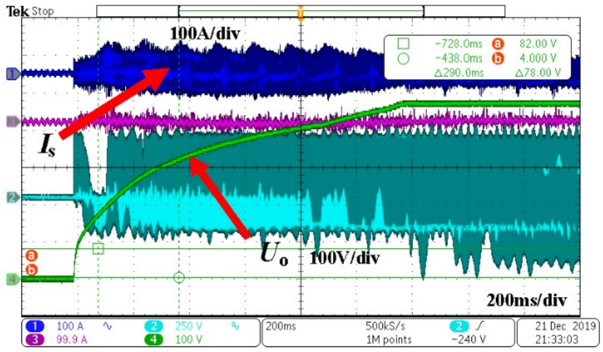


Figure 11. Experiment waveforms with novel start-up strategy.

6. Conclusion

In this paper, the current stress problem in 3p-DAB converter during the start-up process under heavy load condition is analysed. A new start-up control strategy with the coordinated action of duty-cycle and phase shift angle for 3p-DAB is proposed. This startup strategy can reduce the current stress of the startup process without adding additional circuits. Finally, the theoretical analysis is verified by the simulation and experiment results.

Acknowledgments

This work was supported by State Grid Co., Ltd. Science and Technology Project: Research and Demonstration on Key Technologies and Operation Evaluation of Charging/Battery Swap Infrastructure for Multiple Application Scenarios under the “Internet +” Business Model (Project No. SGGR0000DLJS1800118).

References

[1] Zhao B, Song Q, Liu W and Sun Y 2014 Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System *IEEE Trans. Power Electron.* **29** 4091–106

[2] De Doncker R W A A, Divan D M and Kheraluwala M H 1991 A three-phase soft-switched high-power-density DC/DC converter for high-power applications *IEEE Trans. Ind. Appl.* **27** 63–73

[3] Hu J, Cui S, Wang S and De Doncker R W 2020 Instantaneous Flux and Current Control for a Three-Phase Dual-Active Bridge DC–DC Converter *IEEE Trans. Power Electron.* **35** 2184–95

[4] Y.Li and W.Meng 2013 On the Precharging Process for EV *Auto Electr. Parts* 8–10

[5] X.Jiang 2006 *Research on the Topology Theory and Control Technonogy of Isolated Boost Full Bridge DC-DC Converter* (Institute of Electrical Engineering, Chinese Academy of Sciences)

[6] Y.Fu, J.Li, W.Hu and M.Lei 2019 Neutral Leg Control and Soft-Start Design of 3-Phase 4-Wire on-Board Bidirectional Charger under Imbalance Load Condition *Trans. China Electrotech. Soc.* **34** 5176–88

[7] Giuliani F, Delmonte N, Cova P, Costabeber A and Castellazzi A 2015 Soft-starting procedure for dual active bridge converter *2015 IEEE 16th Workshop on Control and Modeling for Power Electronics (COMPEL)* pp 1–6

[8] Y.Pan, S.Yuan, A.Chen and C.Zhang 2017 A soft starting method for the isolated DC/DC converter in DC distribution systems *J. Shandong Univ. Sci.* **47** 37–42

[9] Pugliese S, Buticchi G, Mastromauro R A, Andresen M, Liserre M and Stasi S 2020 Soft-Start Procedure for a Three-Stage Smart Transformer based on Dual Active Bridge and Cascaded H-Bridge Converters *IEEE Trans. Power Electron.*

[10] von den Hoff D and De Doncker R W 2019 Instantaneous Start-Up and Shutdown Method for Three-Phase Dual-Active Bridge DC-DC Converters *2019 IEEE Energy Conversion Congress and Exposition (ECCE)* pp 5210–6

[11] Hu J, Cui S and De Doncker R W 2018 DC Fault Ride-Through of a Three-Phase Dual-Active Bridge Converter for DC Grids *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)* pp 2250–6