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A TUNED CLC NETWORK ANALYSIS FOR A CLOSED LOOP HYBRID PHASE SHIFT CONTROLLED DUAL ACTIVE BRIDGE CONVERTER

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ABSTRACT
This paper proposes a resonant dual-active bridge (DAB) converter, which uses a tuned capacitor–inductor–capacitor network. In comparison to the conventional DABs, the proposed topology significantly reduces the bridge currents, lowering both conduction and switching losses and improving the bridge power factors. A mathematical model, which predicts the behavior of the proposed system, is presented to show that both the magnitude and direction of the power flow can be controlled through either relative phase angle or pulse width modulation of voltages produced by the bridges. A mathematical model, which predicts the behavior of the proposed system, is presented to show that both the magnitude and direction of the power flow can be controlled through either relative phase angle or pulse width modulation of voltages produced by the bridges. The viability of the proposed concept is verified through simulation. Experimental results of a 4- kW prototype converter, which has an efficiency of 95% at rated power, are also presented with discussions to demonstrate the improved performance of this topology. In addition, the proposed control plot does not fundamentally build the conduction losses in correlation with the expanded EPS control. In this way, the modified DAB can work efficiently. The topology deduction are first known. At that point, the EPS and TPS regulations are connected, and the comparing working standards and qualities, including the switching, power transfer, and root-mean-square current, are investigated in detail with the help of MATLAB Simulink software with complete results with dynamic response.

1. INTRODUCTION

GLOBALLY there has been an increased concern in the unsustainable manner in which we meet our electrical energy needs. Concerns lie mainly in the way that we are depleting natural resources such as oil and gas while polluting the environment as we extract energy from these unrenewable sources. This has resulted in electricity increasingly being generated rom renewable energy (RE) sources like wind, hydro, tidal, and solar [1]–[4], to address these concerns. Conventionally, large-scale RE generation plants, such as solar and wind farms, have been built and incorporated into the main grid. Efforts to reduce transmission losses have resulted in a shift toward microscale distributed generation (DG) from RE sources [5]–[7]. Power generation through microscale distributed RE sources is highly variable in nature mainly due to the dependence of generation on climate conditions [8]. Some form of energy storage is, therefore, an essential and integral part of most, if not all, RE systems to alleviate the mismatch between electricity supply and demand. Electric vehicles (EVs), which initially emerged as an environmentally friendly and efficient means of transport, can also help to provide power network stability in the presence of these fluctuations when used as vehicle-to-grid (V2G) power sources. EV use in RE systems to supplement energy storage, which is referred to as 'Living & Mobility' [9], essentially requires a bidirectional power interface between the local grid and the EVbattery to allowfor charging the battery when surplus energy is being generated and for extracting energy when there is a deficit. To facilitate a V2G connection with the utility grid requires the use of an ac–dc converter stage, known as a "grid inverter," along with a dc–dc converter, which is also required to be

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bidirectional. The grid inverter is controlled to maintain a constant dc-link voltage either by extracting power from the grid or delivering power to the grid. When the dc–dc converter is delivering power to the load, the grid inverter functions as a rectifier, whereas when the power flow is reversed it works as an inverter generating power at grid frequency.

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Various DAB converters employing a form of series resonance have been investigated, some with phase control and fixed frequency and some with frequency control. In a correlation with frequency of DAB variation in [4], the authors reasoned that the main preferred of the last was its lower current effect and reduced losses. Also, series resonant DABs typically require a more complex control system, particularly when they are required to operate with wide load and supply voltage variations. All current AB converters in a general draw a high current at full power component, and along these lines, bring losses. As an answer, this paper displays a novel

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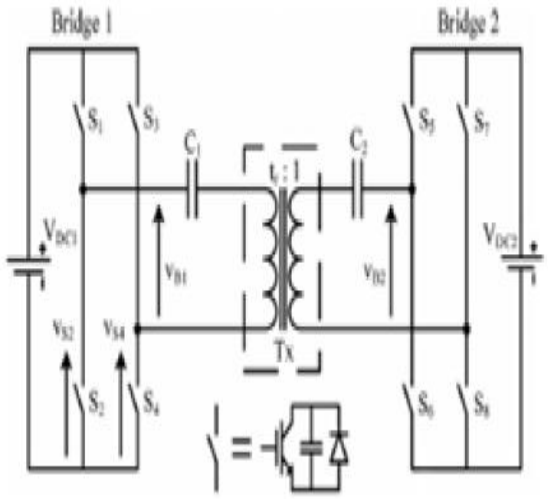

Fig. 1. Proposed Resonant DAB Converter

DAB converter topology, which uses a system to limit the power in bridges. While the proposed converter is conceptually similar to the LCL DAB proposed in [7], including the simple control scheme employed, this variant employs a tuned capacitor–inductor–capacitor (CLC) network. Also, response of CLC system to voltages delivered by the full-bridge converters is fundamentally unique to that of a DAB utilizing a LCL system. The tuned CLC influences a reduce in magnitude of currents and losses. PWM of single bridge is utilized to control power flow, while phase shift between bridges settled at 90° or – 90°, as indicated by direction of power required. The simulated results together with experiment results acquired from a 4-kW model system, to show the capacity of the proposed topology to exchange bidirectional power at a high productivity for an extensive variety of dc supply voltages and power.

2. PROPOSED RESONANT DAB

The structure of the proposed resonant DAB (RDAB) converter is shown in Fig. 1. There are two full-bridge converters, each of which operates at a fixed switching-frequency *fs* , and outputs a three-level pulse widthmodulated voltage source from its dc supply. The bridges are coupled with a resonant network comprising *C*1 , *C*2 , and transformer *T*x, which also provides galvanic isolation. *T*x has leakage and mutual inductances *L*1 and *L*2 (see Fig. 3), which are an integral part of the resonant network, which is tuned to the fundamental of the switching frequency, as given by

$$(L_1 + L_2)C_1 = L_2C_2/t_r^2 = \frac{1}{\omega_s^2} = \frac{1}{(2\pi f_s)^2}.$$

An alternative implementation would use a tightly coupled transformer, havingminimal leakage inductance, with a discrete inductor in series with the primary. Fig. 2 illustrates the switching sequences used to control the RDAB converter's power flow. All bridge switches are operated with 50% duty at the switching frequency fs , with antiphase switching of the transistors within a leg. A phase displacement

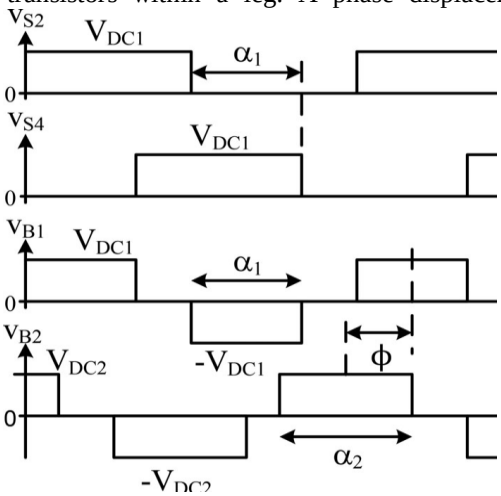

Fig. 2. Bridge voltage waveforms

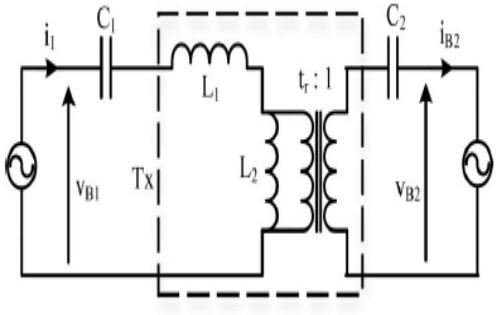

Fig. 3. Initial model.

α1 between the legs of Bridge 1 is used to affect PWM of its output voltage *VB*1 , the

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difference between its leg voltages, as shown in the first three plots. As $\alpha 1$ changes from 0° to 180° *VB*1 's duty changes from 0 to 50%, the latter's square waveform corresponding to 100% modulation. *VB*2 is obtained from Bridge 2 in a similar manner, using modulation $\alpha 2$. The phase-shift φ between *VB*1 and *VB*2 determines the direction of the power flow, and is set to either 90° or −90°, for forward and reverse operation, respectively.

3. CONTROL AND MODES OF OPEARATION

In the first step, the EPS modulation [7] is applied to the modified DAB converter. The gate drive sequences of switches and definition of two phase-shift angles are illustrated in Fig. 4, where us = u2+ u3=2uT, and uT represents the ac voltage applied to the transformer magnetizing inductance. Neglecting the dead time, the upper and lower switches in each switching leg are driven complementarily with a duty cycle of 0.5. The two primary-side switching legs are öp out of phase, the two secondary-side switching legs are driven synchronously, and the phase-shift angle between the primary and secondary units is as ö. With the EPS control, u1 is characterized as an ac rectangular wave with amplitude Vp, and both u2 and u3 are ac square waves with the same amplitude Vs(Vs = nVs).Depending on the relationship between the rising edges of u1 and us, three different operating modes can be identified, as shown in Table I. Operating mode I occurs in both forward Ignoring the dead time, one switching cycle can be divided into six stages, as shown in Fig. 4. Mode I is taken as an example to explore the operation of the modified DAB converter with the EPS control, and due to symmetry, only three stages over the half switching cycle [0, ð] are detailed below.

As aforementioned, the three inductor currents i1, i2, and i3 can be derived with the superposition of the three decoupled currents i12, i23, and i31 which derived by voltages across equivalent inductors L12, L23, and L31 as in Fig. 4. Since the two equivalent ac voltage sources u2 and u3 are synchronous always in the EPS control, the voltage across L23 is zero, and the ac current i23 (è) is equal to 0 in stages. Therefore, ILS (è) equals 0 as well, which means that no current flows through the inserted secondary-side inductor inEPS control, and the operation is the same as the conventional DAB converter. Stage 1 [0, â] [see Fig. 4 prior to this stage, Sp2, Sp3, Ss2, and Ss3 have been conducting. At the onset of this interval, Sp2 is turned OFF and

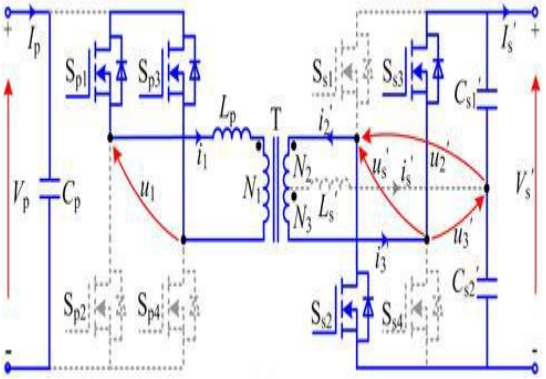

Fig. 4. Stage 1 Operation

theoretically Sp1 is turned ON with ZVS if i1 (0)<0 which means that the antiparallel diode of Sp1 conducts before the transistor does. This interval ends up with Ss2 and Ss3 being turned OFF. During this interval, the two currents i∗12 and i∗31 are expressed as

i12 (θ) = i12 (0) + θ

i31 (θ) = i31 (0) − θ.

Stage 2 [β, α] [see Fig. 3at β, Ss2 andSs3 are turned OFF, and theoretically Ss1 and Ss4 are turned ON with ZVS if i2 (β) and i3 (γ) are negative. This interval ends up with Sp3 being switched OFF at α. During this stage, i12 and i31 are i12 (θ) =i12 (β) − (θ − β)i31 (θ) = i31 (β) + (θ − β)

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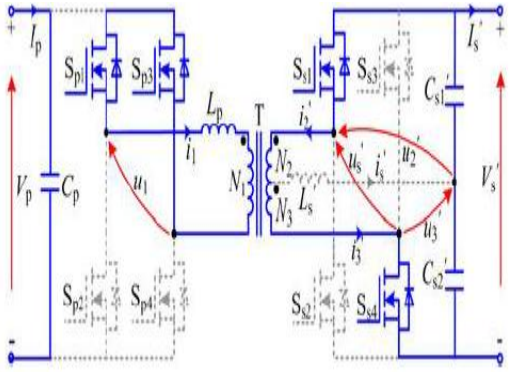

Fig. 5. Stage 2 Operation Stage 3 [α, π] [see Fig. 6 at α, Sp3 is turned OFF, and Ss1 is triggered ON with ZVS if i1 (α) is negative. This interval ends up with Sp1 being switched OFF at π. During this stage, i12 and i31 are i12 (θ) = i12 (α) + (2k −1) (θ − α) i31 (θ) = i 31 (α) − (2k −1) (θ − α) Where the voltage conversion ratio k =VIP/ (n‟s). Thus, i1, i2, and i3 are derived as i1 (θ) = i1 (α) + 2(2k −1) (θ − α) i3 (θ) = i2 (θ) = i2 (α) − (2k −1) (θ − α).

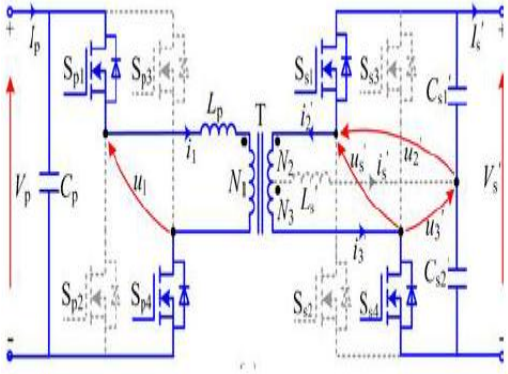

Fig. 6. Stage 3 Operation

Due to modulation symmetry, the upper and lower switches of each switching leg have the same soft-switching condition. Therefore, only Sp1, Sp4, Ss1, and Ss4 are considered, and their switching instants and ZVS conditions are listed in Table II. In order to achieve ZVS operation, the corresponding inductor current at each switching instant should be no more than −IZVS, where IZVS is the minimum current for achieving ZVS within a specified short dead time interval. With the EPS control, time instants β and γ overlapped completely, as shown in Fig.6. By virtue of (10), (12), and (14), the normalized switching currents for each operating mode can be found, as shown in Table III. Theoretically, ZVS turn-on of all devices can be achieved if the inductor currents at four switching instants are less than 0, i.e., IZVS=0 in Table II. Applying ZVS conditions in Table 2, constraints in Table 1 to equations in Table 3, we find phase-shift angle φp should satisfy

φp = π (1−1/ (2k)).

CONCLUSION

A novel DAB topology that employs a *CLC* resonant network has been described. The mathematical model presented has been shown to accurately predict the performance of the proposed topology. Although, the RDAB presented in this paper has not been optimized for efficiency, the results of a 4-kW prototype operated under various conditions suggest a significant improvement in performance in comparison to a conventionalDAB converter with SPS control. The lower bridge currents of the resonant DAB topology result in an increased power capacity and a higher efficiency over a wide range of bridge dc supply voltages. In comparison with the conventional converter'shardware, the RDAB converter requires the addition of two relatively low-cost capacitors and for these to be tuned with the transformer. As a bonus, these capacitors provide dc current reset, preventing core saturation in the event of abnormal operating conditions. In regard to tuning, it has been shown that the converter's operating characteristics are not particularly sensitive to variations in the component values. There is the potential to further increase the operating efficiency by employing a purpose-designed transformer employing a magnetic shunt to affect the required leakage inductance. This transformer will be smaller than that of a conventional DAB converter on account of the lower operating currents.

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