Analysis of Dual Active Bridge Converter in Dual-Phase-Shift mode using Pulse-Width Modulation Technique

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***Abstract*— In this paper, closed-loop control of isolated bidirectional dual-active bridge (DAB) DC-DC converter is proposed for dual-phase-shift (DPS) scheme using fixed frequency pulse-width-modulation (PWM) plus transmitted command power. DPS is a well-known control scheme to reduce backflow power, current stress, and losses, it also provides better power transfer flexibility under high frequency. However, the conventional DPS scheme has limited performance in light load conditions. The discussed control technique overcomes the instant variation of inner phase shift ratio (D_1) w.r.t outer phase shift ratio (D_2) during light load conditions. The theoretical concepts of the transmitted power in different modes of operation are presented in this paper along with a detailed analysis of MATLAB simulation results in dynamic conditions and both directions of power flow. The implemented control scheme leverages most of the improved features of the DPS scheme to transfer power from one end to another end.**

Keywords*— *Dual Active Bridge Converter, Dual Phase Shift, PWM Control, Transmitted command power.

I. Introduction

Emerging technology, such as microgrids is trying to overcome the inadequacy of the traditional grid system. Microgrids are mainly operated in two modes: grid-connected mode and islanded mode [1]. Considering the maximum use of renewable energy sources, it would not be wrong to insist that islanded microgrids should be used as much as possible. Microgrids have their own distributed energy sources, storage systems, and loads with the different electrical profile. Due to different electrical profiles of various sources and loads, dedicated converters are required for interfacing with the microgrid making it reliable, beneficial, and flexible. Bidirectional DAB converter has become the most promising choice for interfacing battery with DC bus in a DC microgrid due to its higher power capacity, soft switching operation, and higher efficiency [1]-[4], [5]. The bidirectional power transfer capability of the bidirectional DAB converter essentially improves the flexibility of the microgrids by reducing the number of converters for the same operation.

Two control methods namely, PWM control and phase shift control methods, are frequently used to control the bidirectional DAB converter. The PWM control technique is a well-established control technique for a bidirectional DAB converter. In this method, linear controllers like proportional and integral (PI) controller modulate the PWM duty cycle of semiconductor switches for voltage regulation and power balancing. Traditionally, the PWM control technique turns on only one side of the H-bridge's cross-connected switch pair. On the other side of H-bridge, only diodes are conducting with switches in the turned-off condition [2]. Although the PWM control technique shows superiority over the phase-shift condition in soft-switching range and reduction in root-mean-square (RMS) current, during load change from full load to light load, the transition between dual PWM to single PWM deteriorates the smoothing operation of the converter. Also, the performance of dual PWM is not at par with the phase-shift technique during the light load condition [6]. However, the phase shift scheme uses phase-shift ratios between the two H-bridges to transfer power from the one bridge to another. The single-phase shift (SPS) scheme is the most popular method due to its simplicity, fast dynamic response, and straightforward implication. In SPS, phase shift ratio D_2 is introduced between the primary and secondary square shape voltage of the transformer to control the magnitude and direction of power transfer in the DAB converter [2],[7]-[9]. However, in the case of voltage mismatch across the transformer windings, a high circulating current flows which lead to high power loss and low efficiency [9],[10]. Therefore, in the recent decade, a variety of phase-shift control methods such as extended phase shift (EPS), DPS, and triple-phase shift (TPS) have been researched to address the above-discussed issues [7], [10]-[19]. However, each control techniques offers a particular advantage over other schemes, making it difficult for the control designer to choose any particular scheme.

Despite several disadvantages, the SPS control scheme provides better dynamic response and freedom of implementation compared to the PWM control technique [8]. In [2], a novel EPS control method is discussed, which has better performance than SPS in terms of the range of power transmission, backflow power, lower conduction losses, and current losses. However, to improve the dynamic response, paper [18] uses another EPS scheme in which an optimized power flow controller is used with EPS to improve the dynamic response and efficiency. Both EPS and DPS have an

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extra phase-shift D_1 in addition to the D_2, which significantly reduces the backflow power and enhances the range of transmission power compared to SPS [2], [15]. In paper [15], a novel DPS is used to reduce reactive power during the operation, which is SPS's inherent property. This paper also claims that the DPS improves the steady-state response and the system's dynamic response with an increase in overall efficiency.

It has been observed that the transmission of constant power and dynamic performance of conventional DPS controlled scheme does not show adequate results at the time of light load conditions. DPS has many control variables that change the command signal to adjust transmission power. Out of this, the operating range of D_2 plays a significant role in varying the command signals. To overcome this issue, paper [17] offers a novel DPS scheme in which command-based power with a bidirectional inner phase shift in place of a unidirectional inner and almost fixed range D_2 value is used to calculate D_1 . This scheme offers a constant transmission power and improves the dynamic response of the system during a light load condition with better efficiency. The performance comparison of the proposed method with any other control scheme is not being discussed. However, the paper [11] has tried to give a comparative result based on almost all the facts such as the range of transmission power, backflow power, and voltage variation and present the DPS control scheme as a better control scheme rather than SPS and EPS.

Although a variety of control methods are available to control the bidirectional DAB converter. However, separate implementation of PWM and phase shift control causes unsatisfactory results, and their control and design requirements, which are also very complex. To mitigate these issues, transmitted command power, and almost fixed range D_2 based fixed-frequency PWM control schemes for DPS mode open a new door of concepts to keep transmission power constant with good dynamic performances. The basic structure of the bidirectional DAB converter and comparative analysis of transmission power of SPS, EPS, and DPS is discussed in section II while the PWM generation logic along with control topology is presented in section III. The analysis of MATLAB-simulation results is discussed in section IV and section V gives the conclusion of all simulation and theoretical analysis.

II. Transmission Power in Different modes of DAB Converter

A typical schematic of isolated bidirectional DAB converter is shown in Fig .1, which has two symmetric H-bridges (H1, H2) coupled to an n:1 turns ratio of the high-frequency transformer with an auxiliary inductor (L_K) and C_1, C_2 are two DC capacitors. V_P and V_S are the equivalent ac voltages of the bridges H1 and H2 at the transformer primary and secondary terminal respectively, and L is the sum of auxiliary inductance and transformer leakage inductor. In this paper, the power flow direction is taken from V_1 to V_2 (i.e., forward direction) as a reference to explain the bidirectional DAB converter's operation under the DPS control scheme.

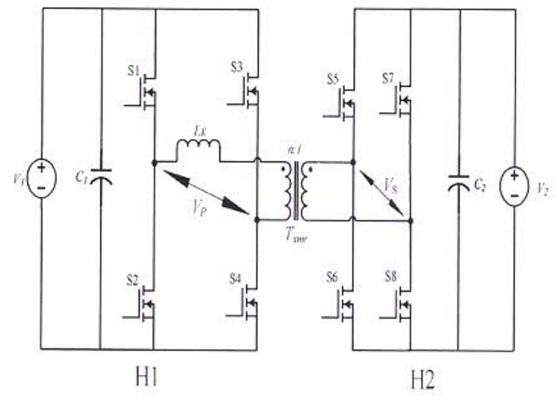

Fig. 1. Typical schematic of isolated bidirectional DAB DC-DC converter.

A. Comparative Analysis of Transmission Power

1. SPS

In case of SPS controlled bidirectional DAB converter if all the factor discussed in the above section is considered as a non-variable parameter then the power flow from one end to another end directly varies with the outer phase-shift ratio D_2. According to the traditional concept of the SPS control scheme, the transmission power (P_1) of the bidirectional DAB converter is formulated as:

$$P_1 = \frac{nV_P V_S}{2f_s L} D_2(1 - D_2) \tag{1}$$

where f_s is the switching frequency, and D_2 lies between 0 to 1. In the SPS control scheme, the transformer primary and secondary voltages will have a fixed pulse width of $T_s = \frac{1}{2f_s}$ [3],[4].

2. EPS

In the EPS scheme, the only primary or secondary voltage of the transformer shows a three-level voltage pattern with a fixed duty ratio i.e. 50% instead of a square wave pattern (two-level). Like the SPS, D_2 $(0 \le D_2 \le 1)$ of the EPS scheme, control the magnitude and direction of power flow (forward mode or reverse mode). However, the D_1 $(0 \le D_1 \le 1)$ is used to minimize the circulating current, and it also improves the regulating flexibility of power. The EPS scheme may have infinite pairs of D_1 and D_2 for the same transmission power. Although neither of both variables is specifically specified, their sum should follow this condition $0 \le D_1 + D_2 \le 1$. The EPS controlled bidirectional DAB converter can be operated under two phase-shift condition $0 \le D_1 \le D_2 \le 1$ and $0 \le D_2 \le D_1 \le 1$. However, the global minimum and maximum value of the transmission power is recorded at $D_1 + D_2 = 1$ and $D_1 + D_2 = 0.5$ respectively. Sometimes either of the two variables is specified for the same transmission power and another variable that is not specified is responsible for controlling transmission power. The transmission power (P_2) of bidirectional DAB converter under EPS is as follow [2], [11], [18]:

$$P_2 = \frac{nV_pV_s}{2f_sL}\left[D_2(1-D_2) + \frac{1}{2}D_1(1-D_1-2D_2)\right] \quad (2)$$

It can be inferred from equation (2) that it becomes difficult to obtain the relation between D_1 and D_2 which can be directly utilized for the system to obtain computational results. However, paper [18] uses a Lagrange multiplier to achieve the relationship between D_1 and D_2. The relationship for the phase shift condition $0 \le D_2 \le D_1 \le 1$ is as follows:

$$\begin{cases} D_1 = (k-1)\sqrt{\frac{1-P_u}{k^2-2k+2}} \\ D_2 = \frac{1}{2} + \frac{k-2}{2}\sqrt{\frac{1-P_u}{k^2-2k+2}} \end{cases} \left(\frac{2k-2}{k^2} < P_u \le 1\right) \quad (3)$$

where $k = V_1/nV_2$ i.e., voltage conversion ratio and P_u is the unified transmission power under the EPS control scheme. However, the relationship for the phase shift condition $0 \le D_1 \le D_2 \le 1$ is as follows:

$$\begin{cases} D_1 = 1 - \sqrt{\frac{P_u}{2(k-1)}} \\ D_2 = \frac{1}{2} + \frac{k-2}{2}\sqrt{\frac{P_u}{2(k-1)}} \end{cases} \left(0 \le P_u \le \frac{2k-2}{k^2}\right) \quad (4)$$

3. DPS

Unlike the EPS mode, in DPS mode, both H-bridges have the same internal phase shift ratio i.e., D_1 between their cross-connected switch pair and external phase shift ratio D_2 between the top switches of both H-bridges [2],[15]. Both transformers' primary and secondary voltages are three-level voltage waveform. As discussed in the introduction section, these two common control variables D_1 and D_2 should be in the range between 0 to 1 and their sum must be less than or equal to 1 ($D_1 + D_2 < 1$). If the sum is greater than 1, the outer phase shift is unable to control the power flow. In DPS, D_1T_s and D_2T_s represent the inner phase shift angle and outer phase shift angle respectively, where $T_s = \frac{1}{2f_s}$ represent the half switching period. The voltage waveform of H1 and H2 of a bidirectional DAB converter under DPS mode can be either lagging or leading depending upon the mode of their operation i.e., forward mode and a reverse mode respectively. In forward mode, power is transferred from high voltage dc bus to the battery of the dc microgrid through the bidirectional DAB converter. The DPS controlled bidirectional DAB converter can transmit power under two phase-shift condition $0 \le D_2 \le D_1 \le 1$ and $0 \le D_1 < D_2 \le 1$, and the switching waveform for phase-shift condition $0 \le D_2 \le D_1 \le 1$ is shown in Fig. 2. The transmission power (P_3) under DPS mode in DAB converter for both phase-shift conditions can be expressed as follows:

$$P_3 = \begin{cases} \frac{nV_pV_s}{4f_sL}(2D_2(1-D_2) - D_1^2) & 0 \le D_1 \le D_2 \le 1 \\ \frac{nV_pV_s}{4f_sL}(2D_2(1-D_1) - D_2^2) & 0 \le D_2 < D_1 \le 1 \end{cases} \quad (5)$$

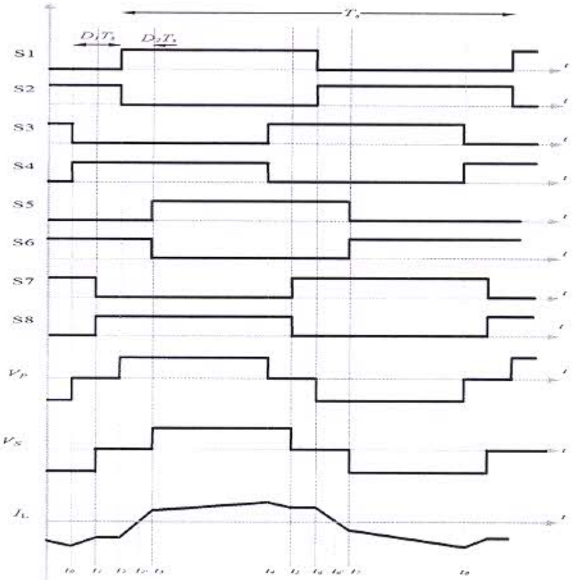

Fig. 2. Switching waveform of DAB converter in the DPS scheme in $0 \le D_2 < D_1 \le 1$ condition.

For the same transmission power, there may be infinite combinations of (D_1, D_2) with a wide range of efficiency. Therefore, it is a little bit difficult to obtain that unique combination of D_1 and D_2 at which all parameters such as efficiency, current stress, backflow power, conversion ratio, steady-state, and the dynamic response would be in the acceptable range [3],[8],[17],[19]. Also, under closed-loop operation in the DPS control scheme, the symmetrical control of both variables concerning transmission power and reactive power creates complexity for the controller. Therefore, in a few works, it has been suggested to fix either D_1 or D_2 value and control another one by a linear controller or any other control algorithms [15],[16]. However, researchers have no strong recommendation at what value one of the variables should be fixed. In some literature, D_1 is initially 0 and D_2 is varied to achieve targeted transmission power with subsequent change in D_1, but lack of information regarding the relationship between D_1 and D_2 makes this system less result-oriented. Hence, it is better to use both variables from the beginning, and to reduce complexity, one of the variables should be fixed within a range (lookup table), and another unknown variable should be controlled accordingly. Let, here, the variable D_1 or D_2 is kept fixed. It is quite easy to obtain another unknown variable (D_1 or D_2) value by using the proper relationship between power and fixed value control variable value (D_1 or D_2). Let assume the value of D_2 is fixed for the transmission power P_3, then the value of D_1 is as follow [16],[17]:

$$D_1 = \begin{cases} \sqrt{2D_2 - 2D_2{}^2 - \frac{P_3}{K}}, & 0 \le D_1 \le D_2 \le 1 \\ 1 - \frac{D_2}{2} - \frac{P_3}{2D_2K}, & 0 \le D_2 < D_1 \le 1 \end{cases} \quad (6)$$

III. Proposed PWM Plus Phase-Shift Control Method

A. PWM Generation & Control Methods

As discussed earlier, the two control variables D_2 and D_1 of DPS scheme can have infinite combinations; hence, deciding the upper and lower values of D_1 and D_2 open up a wide research area. Although, D_1 is very sensitive w.r.t D_2 according to eq. (6) and a small change in D_2 leads to a change in D_1 as well as transmission power. Sometimes, under light load conditions a slight variation in D_2 causes a significant change in D_1 and leads the DPS control scheme to exceed the threshold limit $(D_1 + D_2 < 1)$.

Hence, in this proposed control scheme, a fixed D_2 value and command-based transmitted power is used to calculate D_1 value. Here, the phase shift condition is $0 \leq D_2 < D_1 \leq 1$ for which transmission power P_3 is formulated in eq. (5); and D_1 is calculated from eq. (6) using the measured transmitted power. As shown in Fig .3, control action starts with the PI controller for both modes, an instantaneous output voltage of the DAB converter is measured and feedback to the input of the control block for comparison, where the input voltage is treated as reference voltage i.e., V_{ref}, and its value varies according to the operating mode and input source voltage. The compared error signal is passed to the PI controller. The output of the PI controller is added with the current transmitted power P_{out}. The P_{out} is continuously updating its value according to the regulating value of D_1 and input voltage. Due to closed-loop control action, the continuously changing error signal at the input of the PI controller is completely resolved, and a nearly negligible error value or almost zero value is coming out from the output of the PI controller. At that moment, current transmitted power which is the required transmission power of the system, is obtained at the output of the adder. Here, the control topology that uses fixed D_2, regulates D_1 according to power demand, and such a control scheme enhances the operating range of D_1.

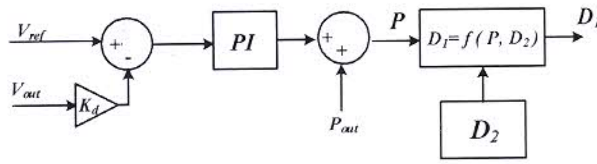

Fig. 3. Command Power Control Block.

The implemented PWM technique generates four principle control pulses P_1, P_2, P_3 ,and P_4 , as depicted in Fig. 4. The PWM pulses of both legs of the primary side H-bridge are shifted by 180° to each other. The output of the control block i.e., D_1 , determines the duty cycle of top switches in both H-bridges. However, the pulse of the secondary H-bridge active leg is phase-shifted by the outer phase shift ratio D_2 ,and the passive leg of the same H-bridge is 180° phase-shifted to the active leg pulses [19].

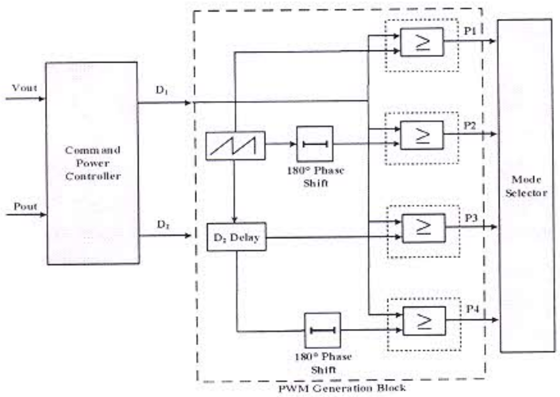

Fig. 4. PWM Generation Block.

B. Mode selector

As already mentioned in the paper, the bidirectional DAB converter operates in forward and reverse mode according to the power demand. Here, the principle control pluses such as P_1, P_2, P_3 ,and P_4 are utilized to switch over the operating mode of the bidirectional DAB converter. Table I explains the working pattern of the mode selector. The bottom switches of both H-bridges are 180° phase-shifted with the corresponding top switches of the same leg. In forward mode, P_1 and P_2 pulses are used to generate the PWM pulses of S1-S2, S3-S4 respectively and S5-S6, S7-S8 are produced by P_3, and P_4, respectively. Moreover, in reverse power transfer mode, P_1 and P_2 make the PWM pulses for S5-S6, and S7-S8, respectively whereas S1-S2, S3-S4 are generated by P_1 and P_2 respectively.

TABLE I: MODE SELECTOR

Mode	P_1	P_2	P_3	P_4
Forward mode	S1	S3	S5	S7
Reverse mode	S5	S7	S1	S3

IV. Matlab Simulation Analysis

A 500 W DAB converter with the discussed control scheme is designed, and major parameters of the converter are presented in TABLE II. The designed converter is simulated in MATLAB Simulink with a solver step size of 6.66 e^{-8} s and operates under the phase shift control condition $0 \leq D_2 < D_1 \leq 1$ with $D_2 = 0.09595$.

TABLE II: Important Parameters Used in Simulation

Parameters	Value
V_1, V_2	380 V,48 V
n	8:1
C_1, C_2	50 μF, 200 μF
L	10 μH

Here, the simulation results are examined for both modes i.e., forward mode (380 V to 48 V) and reverse mode (48V to

380 V), along with their steady-state and dynamic state responses. The PWM pulses according to the control strategy (in order: S1 to S4 and S5 to S8) for forward mode is shown in Fig .5. In which all the top switches have a duty cycle of around 40% while the bottom switches are operating at a duty cycle of 60%.

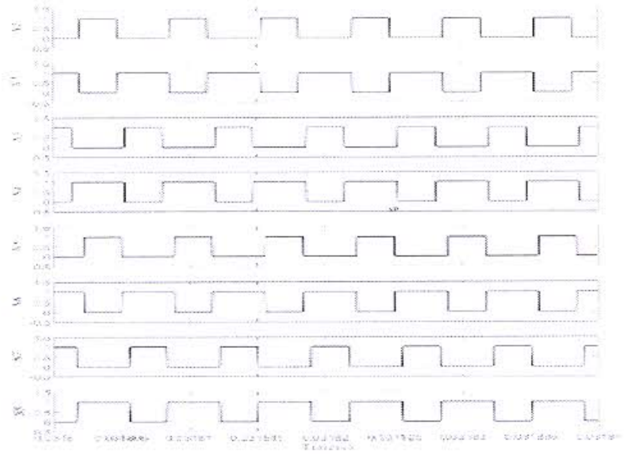

Fig. 5. PWM pulses waveform in forward power transfer mode (380 V to 48 V).

The steady-state and dynamic response of the system in forward mode are shown in Fig. 6 and Fig. 7, respectively. The captured signals in steady-state response are V_P, V_S, the current through L (I_{Ind}), and the voltage across L (V_{Ind}), and here in forward mode, V_S is delayed w.r.t V_P by D_2 as can be seen in Fig. 6. Additionally, V_{Bus}, I_{Ind}, V_{out}, and I_{out} are the captured signals for analysis of dynamic response, where a step-change in load from 100 W to 200 W is introduced at t = 0.025 s, and the converter with discussed control strategy tracks the output reference voltage. For reverse power transfer mode, Fig. 8 depicts the steady-state response depicted, and the captured waveforms are V_S, V_P, I_{Ind} ,and V_{Ind}, where V_P is delayed w.r.t V_S by D_2. However, the captured waveforms are V_{Batt}, I_{Ind}, V_{out}, and I_{out} for the dynamic response, as illustrated in Fig. 9. The reverse power mode is subjected to the same load change at t = 0.035 s, and the controller sets the system output voltage at the rated value.

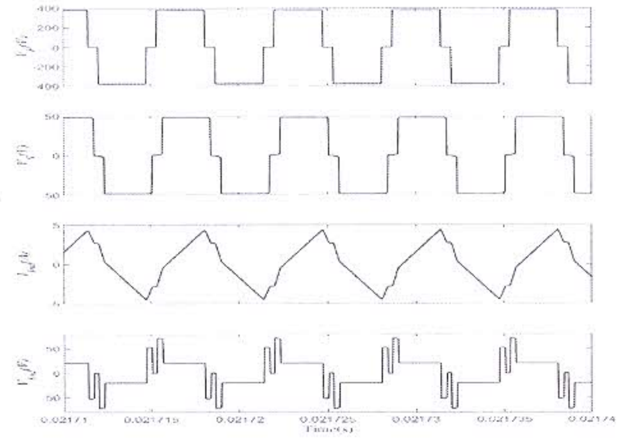

Fig. 6. Steady-state response in forward power transfer mode

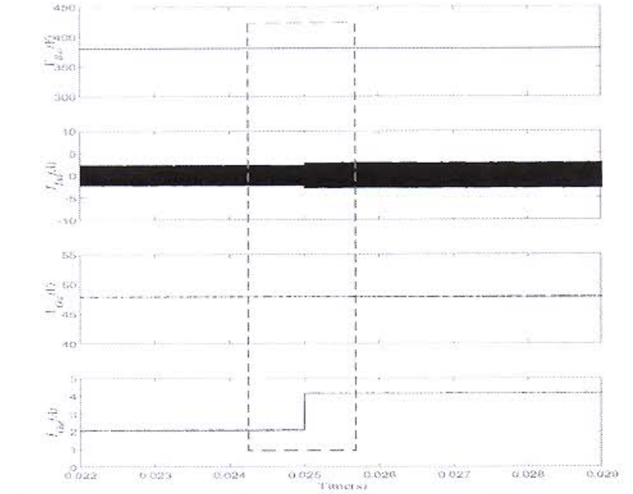

Fig. 7. Dynamic response for 100 W to 200 W load change in forward transfer mode.

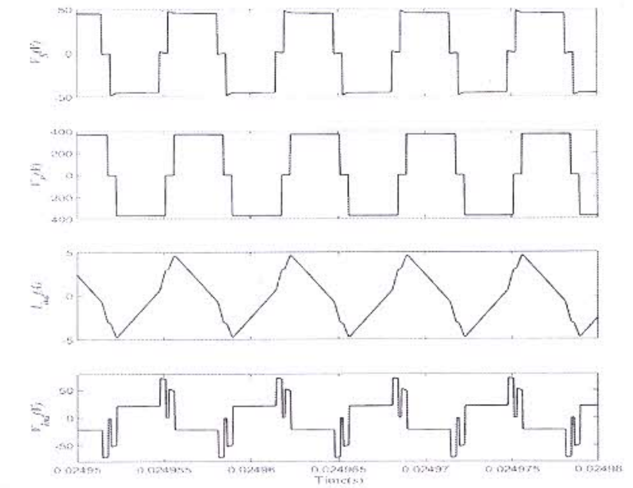

Fig. 8. Reverse power transfer mode steady-state waveform.

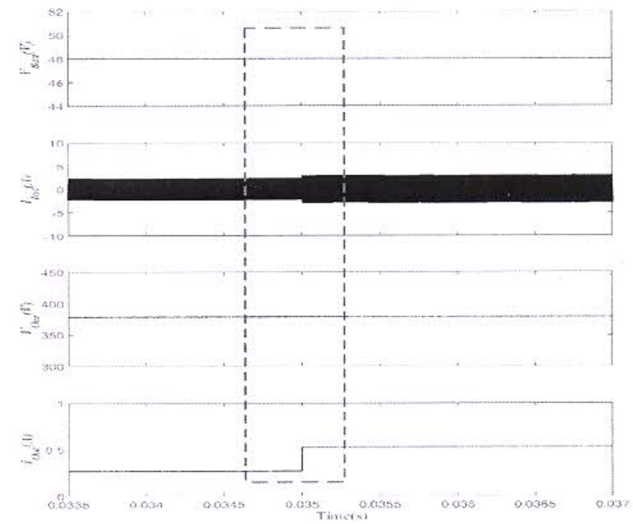

Fig. 9. Dynamic response for load change in reverse transfer mode.

Fig.11 shows the switchover from forward to reverse mode at t = 0.025 s and the capture signals are V_P, V_S, I_{Ind} and V_{Ind}. Initially, DAB converter operates in forward mode at 500 W, and V_S is delayed w.r.t V_P by D_2 and at t= 0.025 s converter switches from forward mode to reverse mode, which forces V_P to be delayed w.r.t V_S by D_2 . Here, the mode selector switch is used to switch over from forward to reverse mode.

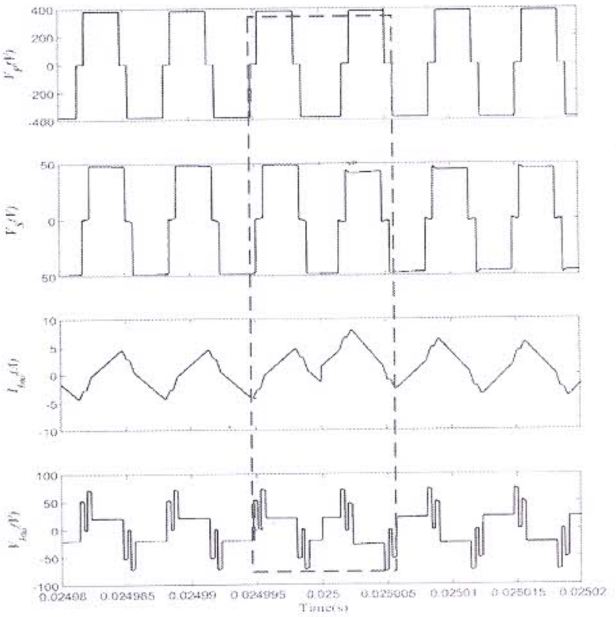

Fig. 10. Mode Change from forward mode to reverse mode

V. CONCLUSION

The PWM plus transmitted control power scheme has been implemented for bidirectional DAB converter in DPS mode, and the MATLAB based simulation has been analysed. The proposed scheme uses command-based power and fixed D_2 value to enhance the range of D_1 within the threshold limit i.e., $(D_1 + D_2 < 1)$, as well as to overcome the instant variation of D_1, which crosses the threshold limit during light load conditions. In terms of implementation complexity, the proposed technique has less complexity than conventional PWM and conventional DPS in every related field, such as calculation of phase shift ratio, mode selection, and generation of switching pulses, it also reduces the design and control complexity of the controller.

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