



## Stable Operation Limits in Dual Active Bridge for SuperCapacitor Applications

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### ABSTRACT

This paper presents an idea for limiting the phase-shift angle in Dual Active Bridge (DAB) which ensures the converter's stability. The stability is the main criterion in a converter's operation without which the converter will stop working. In an ideal DAB which comprises of ideal components, the phase-shift angle limit is  $90^\circ$ . We developed a detailed model in Matlab/Simulink for DAB based on which the limits for the stable operation of converter are derived. In the developed model, attempts are made to employ as accurate as possible models for the components. In this way, the limits are expected to be very close to the practice. The DAB is a bi-directional converter; meaning that the power flow occurs in both forward and reverse directions. We derived the limits separately for forward and reverse modes. It is shown that the limits are the same for both directions confirming the fact that the DAB is symmetrical. We employed the DAB as the SuperCapacitor (SC) energy storage's interface in this paper.

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## 1. INTRODUCTION

Renewable energy sources such as Photovoltaic (PV), Wind, and etc. have fluctuations in their generated power, since they depend on the climate and environmental conditions. On the other hand, there are loads which need constant powers. So, there is always a mismatching between the generation and the demand in renewable energy systems. To resolve this problem, electrical energy storage elements are employed. These elements such as batteries, Supercapacitors (SC), and etc. need interfacing converters which perform their charging and discharging properly. The interfacing converters employed for energy storage elements must be bi-directional to perform both charging and discharging operations [1-5].

The Dual-Active Bridge (DAB) is a bi-directional isolated dc/dc converter as shown in Figure 1. The main reasons for galvanic isolation between sources in multiple-source systems are personal security, noise reduction and voltage matching. The isolation is performed by a high frequency transformer. The DAB is employed in various applications such as renewable energies, power systems, hybrid storage elements,

military equipment, and etc. [6, 7]. In Figure 2, a generic schematic is shown for the isolated bi-directional dc/dc converters.

The DAB is proposed in 1990 for the first time [8, 9]. After many years, the advances in power electronics devices and magnetic materials have resulted in a more efficient converter [10, 11]. The power rating in a bi-directional converter is proportional to the number of switches. Therefore, the power rating in a DAB is more than other types of bi-directional converters such as the push pull, half bridge, and etc. [12].

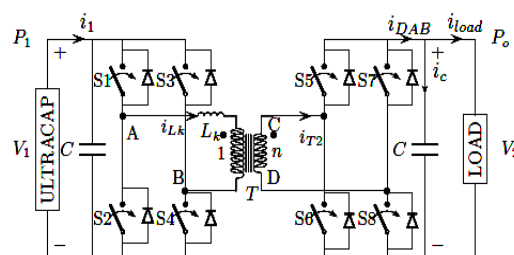
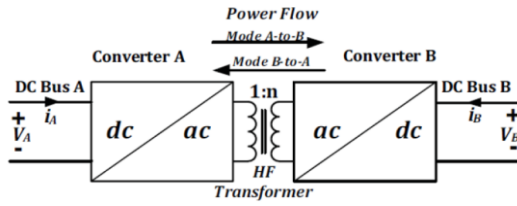


Figure 1. A dual-active bridge utilized for supercapacitor applications

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**Figure 2.** A generic schematic for a dc/dc isolated bi-directional converter

The SCs are among the most advanced energy storage elements. They have features such as high power density, suitable and safe for the environment, low shelf discharge, wide operating temperature range, fast charging and discharging capabilities, high capacities and very high life cycles. Because of the limited energy stored in SCs, their associated converters can operate only at some limited periods of time. This type of converters' operation is called the intermittent operation [13]. They are also combined with batteries and fuel cell which form hybrid energy storage [14].

Base on literature [15-17], the modelling, design, and control of DAB in different conditions and applications are presented. Stability and power transfer analysis of DAB are presented [18-20]. Ghani et al. [21] employed an online particle swarm technique to optimize the DAB phase-shift angle; for a bi-directional dc-dc converter, a current-limit control scheme is presented. The presented scheme aimed to prevent the converter from becoming unstable. The similar work presented by Ahmadi et al. [22] for the DAB; we need to make sure that the converter is prevented from becoming unstable condition. In an ideal DAB, the phase-shift angle limit above which the converter becomes unstable is 90°. Based on this, all of the previous works considered 90° as the stability limit of DAB.

In this paper, by employing a detailed model, we will show that it is not valid to consider 90° as the stability limit of DAB. In fact, we will show that, depending on the converter's parameters, a phase-shift angle less than 90° must be considered as the DAB's stability limit.

## 2. OPERATION PRINCIPLES OF DUAL- ACTIVE BRIDGE

In this section, the operation principles of DAB are presented. The DAB's operation is based on the Phase-Shift Modulation (PSM). This means that the switching signals for one of the bridges are phase-shifted with respect to those of the other bridge.

### A. Different Types of Phase-Shift Modulation

There are four types of phase-shift modulation including the Single Phase-Shift (SPS), Extended Phase-Shift

(EPS), Dual Phase- Shift (DPS), and Triple Phase-Shift (TPS) as discussed by Kayaalp et al. [23]. We employed a SPS as shown in Figure 3 in this paper. As seen, the bridge 2's AC voltage is phase-shifted with respect to the bridge 1's AC voltage. The phase-shift angle  $\varphi$  can be positive or negative. A positive phase-shift angle results in a power flow from bridge 1 to bridge 2 which is called the forward mode of operation. The reverse mode of operation occurs when the phase-shift angle is negative resulting in a power flow from bridge 2 to bridge 1. The DAB with the SPS has the advantages of simplicity and great stability. It also provides the maximum power delivery capability. It has, however, the disadvantages such as lower efficiency and dynamic response compared to the other types of phase-shift modulation [23].

In the SPS modulation, by considering ideal components, the equation for power delivered to the output can be obtained as follows [23, 24].

$$P_o = \frac{nv_1v_2}{2\pi^2f_sL_s} \varphi(\pi - \varphi) \tag{1}$$

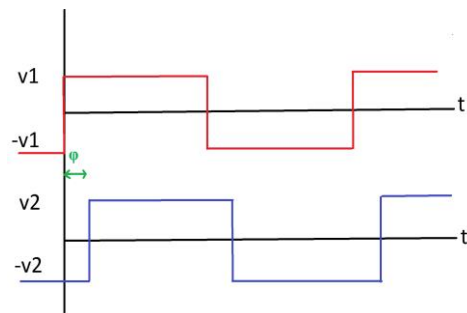
which  $V_1$  is the input voltage,  $V_2$  is the output voltage,  $n$  is the transformer turns ratio,  $\varphi$  is the phase-shift angle in radians,  $f_s$  is the switching frequency and  $L_s$  is the total inductance when everything is moved to the secondary of transformer. It can also be shown that the following equation can be derived for the output voltage.

$$V_2 = \frac{nv_1}{2\pi^2f_sL_s} R_L \varphi(\pi - \varphi) \tag{2}$$

where,  $R_L$  is the load. Based on this equation, for fixed  $V_1$  and  $R_L$ , the output voltage is dependent on the phase-shift angle  $\varphi$ . So, by changing in  $\varphi$ , the output voltage varies accordingly.

### B. Parameters for Designed DAB

We designed a DAB for the SC's applications with the parameters shown in Table 1 for which the idea of phase-shift angle limiting is presented. We, however, want to confirm that the idea is generic and can be employed for a DAB with any parameters. According to Equation (1),



**Figure 3.** AC side voltages of bridge 1 and bridge 2 with SPS modulation

**TABLE 1.** Parameters of designed DAB for SC applications

Symbol	Description	Value
$L_s(\mu H)$	Total inductance	120
$n = \frac{n_2}{n_1}$	Transformer turns ratio	8
$f_s(kHz)$	Switching frequency	20
$V_{CE}(V)$	On-state IGBT's collector to emitter voltage	3
$V_{FD}(V)$	Forward biased anti-parallel diode voltage	1.6
$t_{db}(\mu s)$	Dead-beat	2
$R_1(\Omega)$	Transformer primary winding resistance	0.06
$R_2(\Omega)$	Transformer secondary winding resistance	0.13
$C_{sc}(F)$	Capacitance of SC	18
$V_1(V)$	Input voltage nominal value	48
$V_2(V)$	Output voltage nominal value	400
$i_{load}(A)$	Output current nominal value	10

the amounts of power delivered to the output in DAB depends on  $V_1$ ,  $V_2$ ,  $n$ ,  $f_s$ ,  $\Phi$ , and  $L_s$ . For a DAB with given parameters, the values of  $n$ ,  $f_s$ , and  $L_s$  are fixed. In order to regulate the output voltage at a desired value, despite the SC's voltage varies, the phase-shift angle must be adjusted appropriately by the closed-loop control system. In the case of a voltage drop at the output, the phase-shift angle will be increased in the positive direction to restore the output voltage. This leads to the SC discharging. Also, in the case of a voltage swell at the output, the phase-shift angle will be increased in the negative direction to restore the output voltage which leads to the SC charging. However, in both cases of DAB's forward and reverse modes, the phase-shift angle must be appropriately limited in order to keep the converter stable.

### C. Limits for Phase-Shift Angle in Ideal DAB

As seen in Equation (2),  $V_2$  versus  $\varphi$  is a quadratic parabolic function whose maximum is obtained if the derivative of  $V_2$  with respect to  $\varphi$  is set to zero. That is:

$$\frac{dV_2}{d\varphi} = 0 \rightarrow \varphi = \frac{\pi}{2} \quad (3)$$

This means that, in the ideal DAB, at the phase-shift angle equals to  $+90^\circ$ , the maximum output voltage is obtained. So,  $+90^\circ$  is considered as the phase-shift angle limit above which the DAB becomes unstable.

## 3. STABLE OPERATION LIMITS FOR NON-IDEAL DAB

In order to obtain the phase-shift angle limits for the stable operation of the DAB, we developed a detailed model in Matlab/Simulink. To have a model close to the reality, we, at the first step, include the power switches'

voltage drops, transformer and inductor windings resistances. We call this model a lossy one without the deadbeat. The model is then equipped with the deadbeat as well.

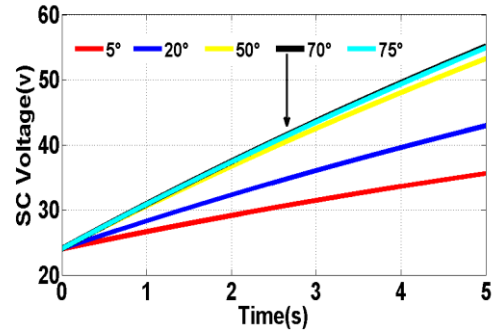
Attempts are made to employ as accurate as possible models for each component. In this way, the obtained limits will be very close to the practice. The model is run in the open-loop mode in which the converter's performance can be evaluated at steady-states for different values of the phase-shift angle.

### D. Lossy Model without Deadbeat

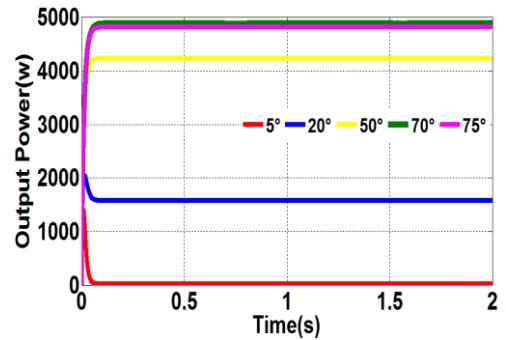
The open-loop simulations of DAB are done in five positive phase-shift angles, i.e.  $5^\circ$ ,  $20^\circ$ ,  $50^\circ$ ,  $70^\circ$ , and  $75^\circ$  which are for the forward mode of operation. Also, five negative phase-shift angles i.e.  $-5^\circ$ ,  $-20^\circ$ ,  $-50^\circ$ ,  $-70^\circ$ , and  $-75^\circ$  are considered for the reverse mode of operation. The results are shown in Figures 4 to 7.

In both cases of forward and reverse modes, we start to increase the phase-shift angle until the exchanged power starts to decrease. The phase-shift angle at which the exchanged power starts to decrease is considered as the limit. We derive the limits separately for the forward and reverse modes.

According to Figures 4 and 5, in the forward mode, by increasing the phase-shift angle up to  $70^\circ$ , the output



**Figure 4.** Output voltage in forward mode for different phase-shift angles



**Figure 5.** Output power in forward mode for different phase-shift angles

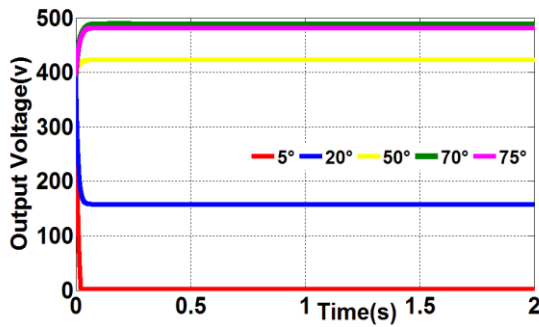


Figure 6. Voltage of SC in reverse mode for different phase-shift angles

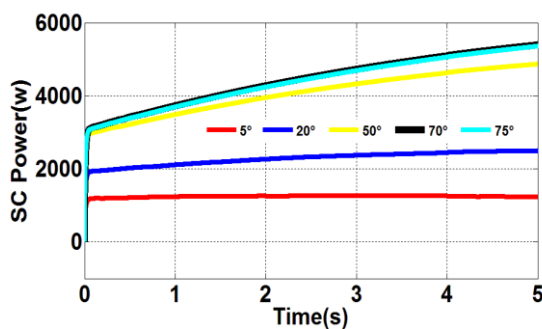


Figure 7. Power absorbed by SC in reverse mode for different phase-shift angles

voltage as well as the power delivered to the output increase. However, for higher phase-shift angles, the output voltage and the power delivered decrease. Therefore, for the stability of converter in this mode, any increase in the phase-shift angle above  $70^\circ$  must be avoided. Note that, tests in the forward mode are performed with nominal input voltage and output current as listed in Table 1.

For the reverse mode, according to Figures 6 and 7, by increasing the phase-shift angle up to  $-70^\circ$ , the SC's voltage as well as the absorbed power by the SC increase. However, for higher phase-shift angles, the SC's voltage and absorbed power decrease. So, the same as the forward mode, in the reverse mode, any increase in the phase-shift angle above  $-70^\circ$  must be avoided in order to keep the converter stable. Tests in the reverse mode are performed with the nominal output voltage and nominal output current injected to the converter's output. Note that, the results in Figures 6 and 7 are dynamic ones, since the SC's charging is in progress. It is also worth mentioning that the limits obtained for the forward and reverse modes are the same implying the fact that the converter is symmetrical.

For different load currents, the output voltage is shown against the phase-shift angle in Figure 8. It is clear that for a specific phase-shift angle, by increasing in the load current, the output voltage decreases which is

expected. Also, for any load current, the output voltage increases as the phase-shift angle is increased until the phase-shift angle reaches the limit, i.e.  $70^\circ$ . Increasing the phase-shift angle above  $70^\circ$  results in decreasing the output voltage and therefore, the power delivered to the output is decreased. This means that  $70^\circ$  is the phase-shift angle limit for the DAB with the listed parameters regardless of the load current.

#### E. Lossy Model with Deadbeat

A  $2\mu\text{s}$  deadbeat is considered for the DAB with the listed parameters in Table 1. It guarantees that no short-circuit occurs in any of the converter's legs. However, it has adverse effects on the converter's performance which are inevitable [25]. In this section, we investigate the deadbeat effects on the power delivery capability as well as the limits of the phase-shift angle.

For a specific load current, the output voltage is shown against the phase-shift angle both for with and without the deadbeat in Figure 9. As clear, in both cases, by increasing in the phase-shift angle, the output voltage increases until the phase-shift angle reaches the limit. The limit equals to  $70^\circ$  for the case of without deadbeat as shown before. It is, however, higher for the case of with deadbeat as clear.

For a specific phase-shift angle, by including the deadbeat, the output voltage is decreased especially at low phase-shift angles as shown. The case gets better as the phase-shift angle increases. This means that, including the deadbeat, which is necessary for the proper operation of converter in practice, has an adverse effect on the power delivery capability of the DAB. We, therefore, want to conclude that including the deadbeat reduces the effective phase-shift angle. As a result of this, the power delivery capability is reduced and the phase-shift angle limit is increased.

In Figure 10, by including the deadbeat, the output voltage is shown against the phase-shift angle for different load currents. As clear, for a specific phase-shift angle, by reducing the load current, the output voltage increases as expected. Also, for a specific load current, by increasing the phase-shift angle, the output voltage increases until the phase-shift angle reaches the limit. As clear, the limit is different for different load currents. In fact, for 1A load current, the limit equals to  $85^\circ$ , for 5A load current, the limit equals to  $80^\circ$ , for 10A load current, the limit equals to  $75^\circ$ , and for 15A load current, the limit equals to  $70^\circ$ . So, by considering 10A as the nominal load current, the limit for the phase-shift angle for the DAB with the listed parameters equals to  $75^\circ$ . Comparing Figures 8 and 10 for 10A load current shows that the phase-shift angle limit is higher for the case of with deadbeat confirming the fact that the deadbeat reduces the effective phase-shift angle. We also want to conclude that the phase-shift angle limit for the reverse mode equals to  $-75^\circ$ , since the converter is symmetrical.

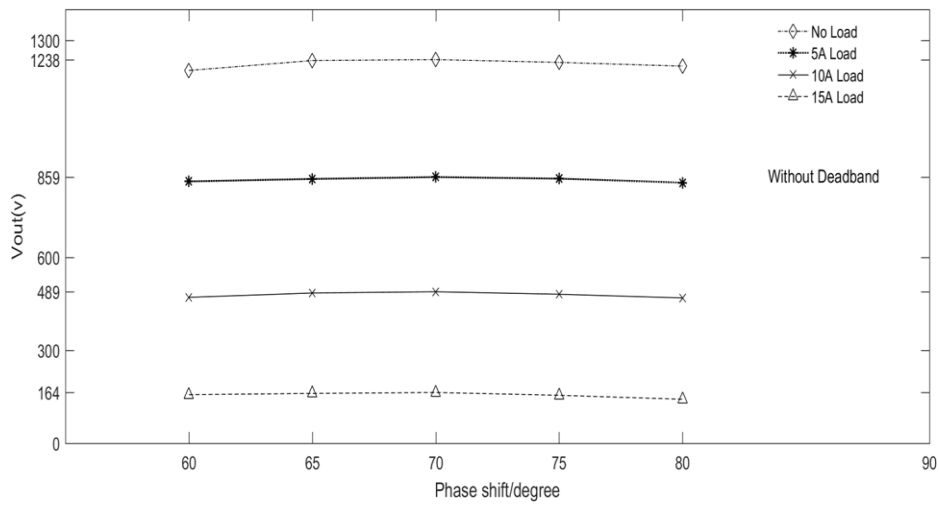


Figure 8. Output voltage versus phase-shift angle for different load currents without including deadband

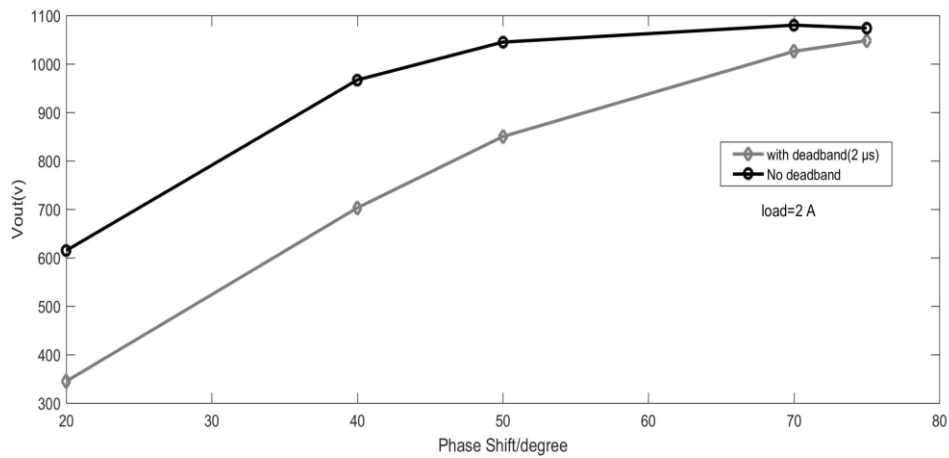


Figure 9. Output voltage versus phase-shift angle for with and without deadband

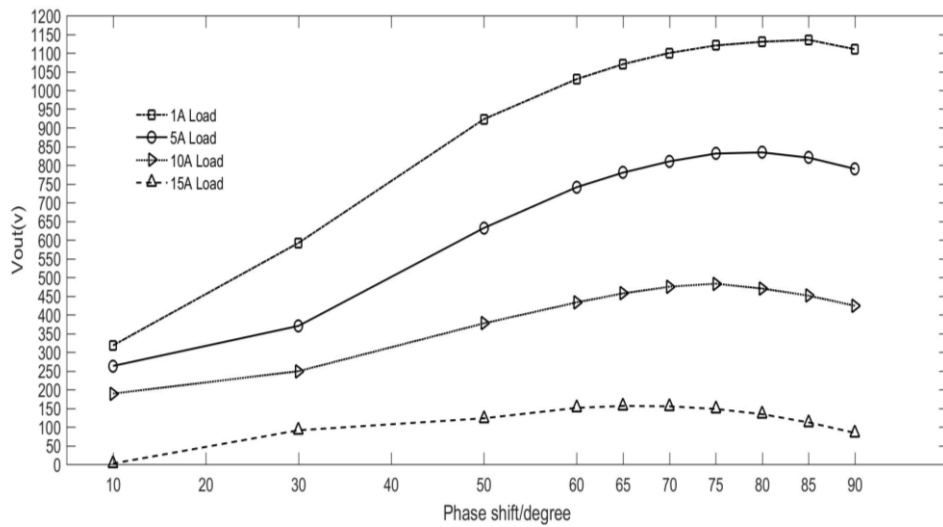


Figure 10. Output voltage versus phase-shift angle with deadbeat for different load currents

#### 4. DISCUSSION

In this section, we present a discussion about the idea of phase-shift angle limiting as well as the results obtained. As said, we limit the phase-shift angle in order to make sure that the converter is stable.

The stability is the main criterion in a power electronics converter's operation. This is because of the fact that, without stability, the converter will stop working soon. So, we limited the phase-shift angle in the DAB according to the stability criterion. There are, of course, other criteria too such as the efficiency, current stress, and etc. However, in the DAB, because of its structure, the efficiency is inherently high. So, it is believed that the most limiting criterion in the DAB's operation is the stability. In the other words, by ensuring the stability, other important criteria such as the efficiency are well met.

For fixed input voltage and output current, the output voltage is shown against the phase-shift angle for different conditions as shown in the previous section. Starting from low phase-shift angles, the output voltage increases as the phase-shift angle is increased up to a certain value. Increasing in the phase-shift angle above the certain value leads to the output voltage decreasing.

This value is considered as the stability limit for the phase-shift angle. This is due to the fact that, the closed-loop control systems' efforts to restore the output voltage, which is through increasing the phase-shift angle in the case of output voltage drop, will result in the output voltage decreasing if the phase-shift angle is moved above the limit. Since the output voltage is not restored, the closed-loop control system increases the phase-shift angle more and more resulting in the output voltage decreasing more and more until the output voltage reaches to zero. The derived limits for the forward and reverse modes, which are the same since the DAB is symmetrical, are employed in the closed-loop control system which guarantees that no increasing above the limits occurs either at dynamic or steady-states [26].

According to Equation (1), imposing limitations on the phase-shift angle means that the maximum power which can be delivered by the converter is accordingly limited. The same happens for the voltage gain as clear from Equation (2). Also, it slows down the dynamic performance of the converter. We call these as the adverse effects of phase-shift angle limiting.

Although the limit for an ideal DAB is  $90^\circ$  regardless of the converter's parameters, the derived limits are for the DAB with the listed parameters. This means that the limits can be different for a DAB with different parameters. So, the same procedure, as shown, must be followed to obtain the limits for any DAB with given parameters. We, however, want to confirm that the derived limits are the converter's characteristics. This

means that they are valid regardless of the converter's application or the converter's input source or output load.

#### 5. CONCLUSIONS

Based on a detailed model developed in Matlab/Simulink, we derived the limits for the phase-shift angle in DAB both for the forward and reverse modes. The operation of converter above these limits must be prevented in order to keep the converter stable. In contrast to the ideal model for which the allowable range of phase-shift angle is  $-90^\circ < \varphi < 90^\circ$ , the non-ideal model's allowable range is  $-75^\circ < \varphi < 75^\circ$  for the converter with the listed parameters. In the non-ideal model, we considered the power switches' voltage drops, transformer and inductor windings resistances, and, of course, the deadbeat. It is also confirmed that the deadbeat reduces the effective phase-shift angle in DAB's operation.

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## 7. APPENDIX

The closed-loop control system for the designed DAB for SC applications is shown in Figure (A-1). It is based on the output voltage control for which a Proportional-Integral-Derivative (PID) control is employed. The output voltage reference value is set to 400V which is the output nominal voltage. The modulator from which switching signals are generated is a Single Phase-Shift (SPS) one as explained before. It generates eight switching signals for the switches in bridges 1 and 2. The switching signal of a switch in bridge 2 is phase-shifted with respect to the switching signal of its counterpart in bridge 1.

The idea presented in this paper for limiting the phase-shift angle is implemented in the closed-loop control system as shown. In fact, we limit the controller output appropriately such that the phase-shift angle does not exceed the obtained limits. Note that, the limits are implemented both for the forward and reverse modes of operation. In this way, we make sure that the DAB's operation is stable.

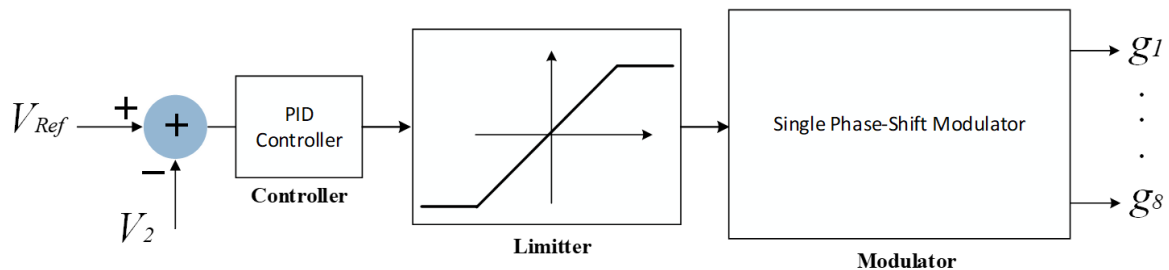


Figure (A-1). Closed-loop control system of DAB with implemented phase-shift angle limits

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**Persian Abstract**

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**چکیده**

در این مقاله به ارائه ایده ای برای محدود کردن زاویه شیفیت فاز در مبدل پل فعال دوگانه با هدف پایداری مبدل پرداخته میشود. پایداری، اصلی ترین معیار در کار یک مبدل است چرا که بدون آن مبدل به سرعت از کار می افتد. در مبدل پل فعال دوگانه ایده آل، محدوده مجاز زاویه شیفیت فاز  $90^\circ \pm$  است. در این مقاله با بکارگیری یک مدل دقیق از مبدل که در نرم افزار Matlab/Simulink ایجاد کردیم به استخراج محدوده مجاز شیفیت فاز می پردازیم. در مدل پیاده سازی شده تلاش شده است تا از دقیق ترین مدل المانها بهره جسته شود و بدین ترتیب بتوان محدوده استخراج شده را به واقعیت نزدیک دانست. مبدل پل فعال دوگانه یک مبدل دوجهته است. بدین معنی که شارش توان در آن هم در جهت مستقیم و هم در جهت معکوس امکان پذیر است. ما محدوده مجاز شیفیت فاز را جداگانه برای کارکردهای مستقیم و معکوس استخراج کردیم هر چند نشان داده شد که محدوده مجاز برای کارکردهای مستقیم و معکوس یکسان است. این موضوع به دلیل وجود تقارن در مبدل است. در این مقاله، مبدل پل فعال دوگانه برای کاربردهای ابرخازن مورد استفاده قرار گرفته است.

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