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Comparative Analysis and Performance Evaluation of Dual Active Bridge Converter Using Different Modulation Techniques

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ABSTRACT- The development in the renewable energy systems and the necessity of the enhanced grid that includes the conventional energy sources and the renewable energy sources and storage systems have realized the importance of power electronics conversion systems. These interfaces are crucial for enhancing the efficiency as well as the control in bi-directional power flow. The use of HEVs as a means of preserving the future supply of fossil fuels, as well as the need for improving the efficiency of the power electronics interfaces required for efficient power management between the two energy sources of the vehicle, is discussed. Furthermore, the improvements in the Uninterruptible Power Supply (UPS) systems and regenerative power systems also require sophisticated power electronic conversion systems. To address these issues of modern technologies, the Dual Active Bridge (DAB) converter comes in as a potential solution. In this paper, several modulation techniques employed in DAB converters are discussed and compared in detail in order to find the best approach to control the converter's performance in the whole range of its operation. The paper also presents an enhanced modulation strategy applied to DAB converters and built with FPGAs and MPC to minimize the power loss. This proposed optimization technique is more general and easier than the current ones. The performance of the converter is assessed in terms of efficiency, current stress, and the power of backflow, in addition to the proposed optimization and modulation techniques. The article also looks at the closed-loop performance under step load fluctuations and circuit performance as well as efficiency.

Keywords: Converter, Efficiency, Phase shift, Optimization, Modulation, Controller and Feedback.

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1. INTRODUCTION

A dual active bridge is a bidirectional DC-DC converter that consists of a high frequency transformer, an energy transfer inductor, and DC-link capacitors in addition to two identical main- and secondary-side full-bridges. The DAB converter is a reliable and efficient high-power DC-DC converters for over 25 years. As a building block for more advanced converters, the DAB converter's fundamental soft-switching, galvanic isolation, and bidirectionality are invaluable. Both the multi-port DAB conversion and the current-fed DAB converter, two contemporary improvements on the original design, have been shown to offer advantages beyond those of the original [1]. Since the DAB converters may be used as the central building blocks in cascade or parallel configurations. The basic layout of a single-phase DAB conversion is shown in *figure 1*. Each bridge in a DAB receives pulses from a 50% diagonal gate, constituting the fundamental modulation mechanism known as single-phase shift (SPS). The dual active bridge (DAB) converter has gained the reputation of being one of the most

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reliable and efficient converters in power conversion. To this end, conventional modulation techniques are known to have their short falls in the sense that they cannot offer their best performance at all the possible operating conditions. This paper presents a new modulation technique based on the implementation of FPGAs and MPC to tackle the issues. The developed method, therefore, intends to enhance the efficiency and reduce the losses of power while being an innovation in the power electronics area.

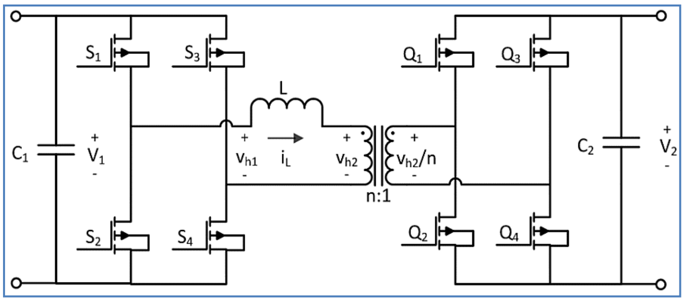

Figure 1. DAB Converters

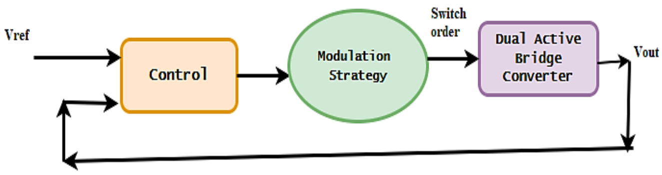

Figure 2. Conventional Controls of DAB

Total inductance, or L*tot*, is the sum of the inductances introduced into the main and secondary windings of the transformer, as well as the leakage inductance. Following is a simplified explanation of the lossless mechanism used by the DAB converter [2]. This method assumes that the magnetizing inductance is infinite, that the switches are faultless, and that the voltage sources are flawless, but it does not account for the resistance and capacitance of the windings.

1.1 Types of Modulation Techniques Used for DAB

The below mentioned principal modulation techniques are traditionally used for DAB. They are

a. Single phase-shift (SPS),
b. Dual-phase shift (DPS),
c. Triple-phase-shift modulation (TPS),
d. Triangular modulations,
e. Trapezoidal modulations,
f. Extended Single-Phase Shift (ESPS),
g. Combinational modulation techniques

In this research, we examine the implications of several modulation methods on the robustness of DAB. It generates and analyses input impedances for the DAB converter using three commonly used modulation schemes [3]. The most effective way of modulation has been identified from the perspective of stability, and this has been confirmed experimentally.

DC/DC converters using DAB technology combine many of the benefits of DC/DC conversion that are available in other, more traditional topologies (Dual Active Bridge). It is essential for a DAB converter to have closed loop control to ensure that its output is consistent throughout a wide range of operating circumstances. A typical DAB converter's control panel is shown in *figure 2*. That divides into two main categories. The first is the venerable control unit, which has seen its fair share of control mechanisms throughout the years [4]. The nonlinear nature of the converter may be accounted for by using a nonlinear control scheme, such as the widely used PI (Proportional Integral) controller. On a deeper level, the modulation block converts the controller's output into the converter's switching order. Single Phase Shift (SPS) modulating is a tried-and-true method, as its name implies, it uses a single-phase shift to determine how much power is sent. This modulation works well for sending plenty of power. Triangular Modulation (TRM) is a different modulation strategy that works well for transmitting a little amount of power.

2. LITERATURE SURVEY

Isolated bidirectional DC-DC converters (IBDCs) act as a pertinent part of a power electronics conversion system. Development in Isolated unidirectional DC-DC converters (IUDCs) lead to evolution of IBDCs. For example, full bridge IUDCs can combine to form a DAB IBDCs. Also, a six-switch topology would include a half-full-bridge IBDC, whereas a five-switch architecture would have a full-bridge forward IBDC. Numerous converter topologies have been identified for the primary and secondary converters [5]. It is common practice to utilize a Flyback converter as an isolated DC-DC converter due to its few numbers of components and lack of output filter inductors. A flyback converter supplies various voltage levels by simply using a multiple output winding transformer. For handling bidirectional power, two unidirectional flyback converters are connected back-to-back and thus form the bidirectional isolated flyback converter. Current-fed push-pull (CFPP) converters are the second most popular isolated bidirectional DC-DC converter topology proposed for application in switch mode power supplies. On the application front, these converters are applied in the field of battery chargers, power factor correction systems, UPS system with battery storage etc. The blocking voltage rating for the switches in these converters is quite high, thus making them costly converters and they are used for voltages below 200V and power below 2KW. Due to their great power density and adaptability, bridge converter is the most often utilized converters in IBDCs. The DAB converter, first proposed in [6], is a small, lightweight, and extremely efficient electronic power conversion device that may be utilized in a bidirectional fashion to transport energy between the source and the power storage element in a smart grid. Generally, phase shifted modulation schemes are mostly implied for control of DAB and are utilized for facilitating soft switching. Soft witching is easily realized in a DAB. Soft switching solutions in the area of DAB are offered to solve the issue of greater circulating current, a decrease in the overall effectiveness of the complete system, and a worsening in the switching range under light load situations. High Frequency Link (HFL) resonance tanks are improved so that the range of soft switching may be increased. The converter is run at a higher frequency and efficiency in [7], which proposes using an LC (Inductor-capacitor) type resonance topology of DAB. It is suggested that the forward and reverse power flows above resonance be modulated using variable frequency modulation [8].

Time varying state- space modeling of SPS based DAB has been proposed earlier [9]. A continuous dynamic model for SPS based DAB was introduced for closed loop control of DAB. The charging and discharging of Li-ion batteries have been suggested to use a single-phase shift modulating approach [10]. The cumbersome DC link capacitor is not needed in the suggested architecture. The suggested topology is provided with simulation and experimental models. Extended phase shift modulation strategy is an improved version of SPS, a detailed analysis of its basic characterization and analysis of backflow power in DAB had been carried out by researchers. A new steady state model of DAB operating in EPS mode in terms of rms value of device as well as inductor current has been derived. Analysis of DAB based Solid state transformer is carried out and peak current, backflow power and complete transmission power mathematical models are established. Application of EPS modulation strategy in aerospace energy storage is also shown. Both SPS and EPS rely on stress applied (inner and outer phases shift) to regulate transmission power, and this reliance was previously explored. Double phase shift modulation strategy is proposed in [11], the mathematical modelling [12], current stress [13], and expansion in zero voltage switching (ZVS) range [14] is also shown. A generalized small signal modeling of TPS based DAB has been presented [15] and a linearized model has been developed incorporating phase shifts with duty ratios. To build a DAB-based multi-input state space model, switching mechanisms are also used [16]. In [17], a TPS-based DAB state space model with many inputs is presented. For use in acausal systems, [18] creates a correct average model of DAB. Suitable for both control and power applications, the created model takes into account the switching dynamics. For design of closed-loop controller with maximized performance, the dynamic modeling of a converter becomes a necessity [19].

In absence of dynamic model of converter, the closed loop controller design becomes a heuristic process with a reduction in the overall efficiency of regulator. A sequence of mathematical equations which describe the relation of system output with respect to input stimuli are defined as the dynamic plant model. Based on its use as a solid-state transformer, [20] provides a thorough comparison of DAB in SPS and EPS mode.

The comparison of DAB is also performed based on peak current strain and transmission power in [21]. Backup power systems, recharging systems, solar technology, and supplemental power supply for traction vehicles all make use of converters. DAB unidirectional DC/DC converter architecture is characterized by low device count, gentle switching, low cost, and good efficiency. This architecture might be used in applications where great power density is needed together with cheap cost, low weight, and good reliability.

3. PROPOSED METHOD

The proposed modulation approach involves the incorporation of an optimization function that is to be implemented in Field Programmable Gate Arrays (FPGAs) and Model Predictive Control (MPC). The optimization function is intended for reducing the power losses and increasing the efficiency of the DAB converter in all operation modes. The FPGA is used to implement the complex control algorithms with high accuracy and the MPC is used to implement a predictive control strategy which modulates the modulation parameters according to the system conditions. The mathematical model of the optimization function is as follows: The following equations and descriptions should be added to the paper: It makes it possible to control the converter's operation in real time and thus achieve better performance than with conventional modulation methods. Soft switching, purchase price operation, and a straightforward circuit design are just a few of the benefits of a DAB dc-dc converter. The DAB converter's modulation has three levels of freedom (*ij*, *ijp*, *ijs*). The difference between both the square voltages across the two bridges is the phase *ij*. The PSM's high circulation current and limited soft-switching range make it unsuitable for applications requiring large voltage swings, such as an interconnect for energy storage and solar systems [22]. Several modifications have been suggested to circumvent this problem. There are two degrees of freedom (*ij*,*ijp*) in single pulse-width modulation (SPWM). DPWM (*ij*, *ijp*, *ijs*) modulating system has three degrees of freedom [23]. Only at low powers can the switching range be enhanced and peak current reduced. Due to their limited power transfer ranges, both modulations need to be combined in order to transmit power over a large area.

3.1 Phase-shift modulation

In the case of dual active high flexible, phase shift is among the simplest modulation methods. D1=D2=0.5 (*i.e.* 2-level switching voltages) are used, constricting the system to a single degree of freedom. The main and secondary sides of the transformer are used to regulate the power flow. Positive power is power that flows from the main to the secondary, while negative power is the opposite. This means that the transmission power may be determined by:

$$P = \frac{V_{in}V_{\text{out}}}{nL_{ac}2\pi F_s}\phi\left(1 - \frac{|\phi|}{\pi}\right) \quad (1)$$

As an example, below you can see a depiction of the waveforms of the switching voltage and inductor current: Maximum power transmission between both the primary and second is achieved at =0.25.

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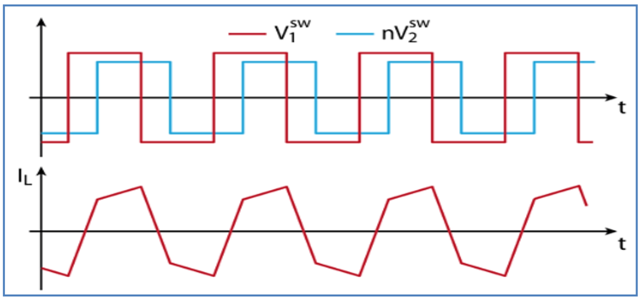

Figure 3. Waveforms of DAB Switched V and I.

Phase-shift modulation is appealing when run near to the operational point where V1=nV2, when the optimum ratio between transmitted power and inductor RMS present is achieved.

3.2 Dual-phase shift (DPS)

PWM voltages are used with dual-phase shift (DPS) programming to power both bridges. The DPS strategy targets the decrease of BFP and current stress and is supported by several optimization techniques [24]. DPS enhances a DAB converter's overall performance in contrast to SPS, particularly when faced with medium and light loads. However, in order to take use of the advantages of the additional degree of freedom that DPS may use, complex mathematical computations are necessary.

3.3 Triple-Phase-Shift Modulation

In comparison to EPS and DPS, the TPSM offers more adaptability since it has three degrees of freedom. According to specific goals, the TPS technique modifies the phase difference and the switching frequency of f vt1 and vt2. TPS is used, for instance, to reduce the stress and BFP that is now present [25]. Despite their many advantages, the optimization of the three parameters involves a significant amount of computational labor and a lengthy implementation process.

3.4 Triangular modulations

It has been shown that triangular modulation is suitable for low power transmission in a DAB converter. The duty ratio of the main voltage, designated as D2, and the initial bridge voltage, designated as D1, may both be used to manage the power flow [26]. According to *figure 3*, the voltage across the leaking inductance in this modulation scheme is either V1 or V2. so (D1+D2) ≤12.

The transfer power is given by:

$$P = \frac{V_{in}^2 D_1^2}{L_{ac} F_s} \tag{2}$$

$$D_1 = \frac{\sqrt{P L_{ac} F_s}}{V_{in}} \tag{3}$$

$$D_2 = D_1 \frac{n V_{in}}{V_{out}} \tag{4}$$

The root-mean-square (RMS) current through leakage inductance may be calculated as:

$$(I_L)_{RMS} = \frac{V_{in}}{L_{ac} F_s} D_1 \sqrt{\frac{2}{3}(D_1 + D_2)} \tag{5}$$

The power dissipation for this modulation may be calculated using the same form as in (5):

$$P_{com} = \frac{K D_1 V_{out}}{n L_{ac}} \left(V_{in} + \frac{V_{out}}{n} \right) \tag{6}$$

As stated in, the triangular modulation (TRG) proposed therein is the most advantageous of all available modulation methods because to its very low switching loss [27]. The leaking inductor current generated by this kind of modulation is triangular in form, thus the name. All turns-on in the TRG technique are handled with soft switching, while six of the turns-off are handled using zero-current switching (ZCS). TRG, however, has a few downsides, the most notable being its limited power.

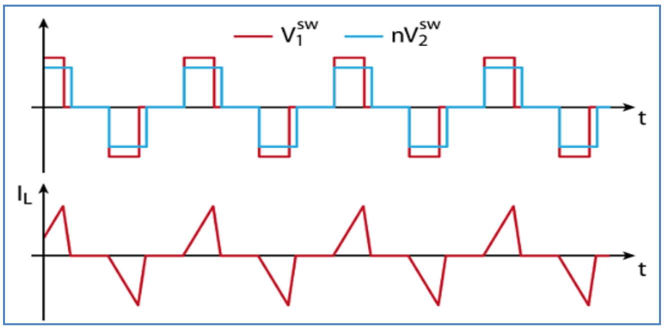

Figure 4. Waveforms of DAB converter operation with triangular modulation

With triangle modulation, both the first and second H-bridges produce switching voltage waveforms with three distinct levels [28]. In this case, the waveform (see graph below) are synchronized at their pulse onsets. Because of this, there is never any current flowing through the second H-bridge switches (ZCS).

3.5 Trapezoidal modulations

By switching to trapezoidal modulation, you may increase the already impressive maximum power transmission of the more common triangle modulation [29]. By using this method, we can achieve ZCS on both the main and secondary H-bridges twice every period. Common waveforms are shown in the examples below. As before, primary and secondary sides' ZCS at relevant moments remains a criterion. V1D1=nV2D2.

$$P_{max}^{tra} = \frac{n^2 V_1^2 V_2^2}{4 f_{sw} L_{tot} (V_1^2 + n V_1 V_2 + n^2 V_2^2)} > P_{max}^{tri} \tag{7}$$

Trapezoidal modulation (TRP) shares its fundamentals with triangular modulation (TRG). All of the switches include soft-switched turn-on, and four of them also feature ZCS upon switch-off. The median power ratios are included in the range of transferrable power that can be achieved with TRP. Using MOSFET switches, SPS is shown to be superior than TRP in all cases [30]. A constant duty cycle marginally affects TRP. Pay that is based on how productive an employee is. The

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modification is situational, and the resulting efficiency boost is marginal.

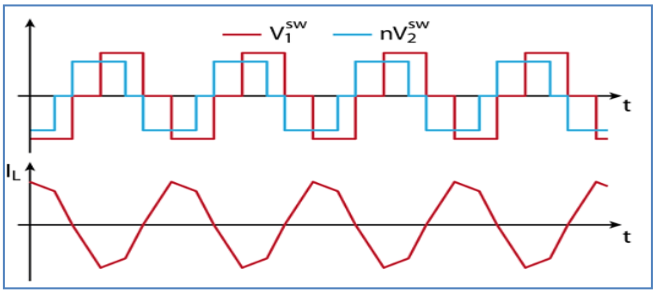

Figure 5. Trapezoidal modulation's effect on the waveforms of a DAB converter's operation

There is a strategy in place to broaden the use of modulating with a single-phase shift. It uses both space-phase modulation (SPM) and time-reversal-modulation (TRM). There are two approaches to take [31]. Mode 1 employs TRM modulation on the first bridge and SPS on the second, as illustrated in *figure 6*.

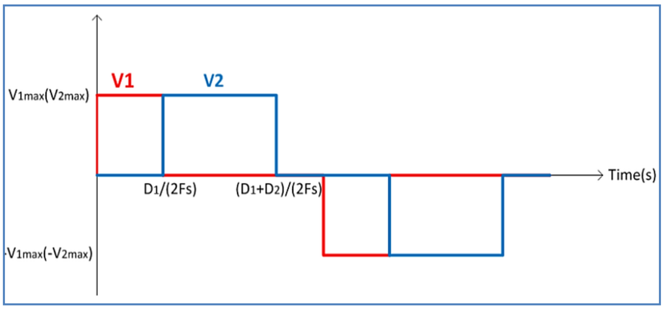

Figure 6. Modulation of the ESPS signal, mode 1

The equation for electricity transmission in both systems is as follows:

$$P = \frac{V_{\text{in}} V_{\text{out}} D_3 (1 - D_3)}{4nF_s L_{ac}} \tag{8}$$

where D3 is the TRM's duty ratio, and it is defined as 0≤ D3≤1⁄2 and its equation is given as:

$$D_3 = \frac{1}{2}\left(1 - \sqrt{1 - \frac{16|P|nL_{ac}2F_s}{V_{\text{in}} V_{\text{out}}}}\right) \tag{9}$$

For mode 1, the RMS current flowing via the inductance is stated as:

$$(I_L)_{RMS} = \sqrt{\frac{n^2V_{in}^2(-13D_3^3+24D_3^2)+nV_{in}V_{\text{out}}(62D_3^3-102D_3^2+18D_3)+V_{\text{out}}(-36D_3^3+63D_3^2-27D_3+11)}{384n^2L_{\text{ac}}^2F_s^2}} \tag{10}$$

Similar expressions for mode 2's RMS current are:

$$(I_L)_{RMS} = \sqrt{\frac{n^2V_{in}^2(36D_3^3+45D_3^2+9D_3+11)+nV_{\text{in}}V_{\text{out}}(-10D_3^3+6D_3^2-18D_3)+V_{\text{out}}(-13D_3^3+24D_3^2)}{384n^2L_{\text{ac}}^2F_s^2}} \tag{11}$$

Finally, switching losses may be expressed as follows:

$$P_{\text{com}} = \frac{KD_3}{2n^2L_{ac}}\left(V_{\text{out}}^2 - (nV_{in})^2\right) \tag{12}$$

In the EPS control, one bridge's switch pairs have an inner phase difference while the other switching pairs are switched similarly to the SPS [32]. The wave patterns of both voltages are switched around in the reverse conduction mode. Numerous scholars have discussed the EPS's performance and guiding philosophy.

5. COMBINATIONAL MODULATION

A combination of strategies may be employed to achieve the highest converter efficiency across a wide range of power. In instance, when the inductor current is zero, a smooth change from triangular to trapezoidal modulation may be made [33]. This enables using both the higher power capabilities of trapezoid modulation when necessary and the great efficiency of triangular modulation at low power. To increase efficiency, the combinational modulation method (CC) is being studied [34,35]. The method employs distinct modulation strategies in various operational zones. At low loads, TRG is used, while SPS is the main modulation method used by the system. In addition, power is transferred via EPS, SPS, and TRG in several various ratios. Thanks to this technology, losses are decreased and efficiency is raised as a result [36]. The technique requires extensive computing computations because of the variable change and the boundary determination.

The modulation approach that we devised is depicted in *figure 5*. The modulation parameters (L_{ac}, F_s, D1, D2 and D3) for each modulation scheme will be derived from the observed voltages Vin, Vout and the controller output that can be converted to a desired power Pref according to *equations (2), (7), (8) and (12)*. With these settings, an FPGA (Field Programmable Gate Array) can simply conduct various modulation patterns to produce acceptable accuracy with a sample time FPGA. The most cost-effective modulation method will be selected using FCS-MPC [37,38]. To calculate the RMS current for each modulation, a predictive model makes use of the power reference, output and input voltages, inductance, predicted value, and switching losses. The word "*" will be used to indicate the predictive factors. Every modulation scheme's cost function is defined as follows:

$$f_{CF}\left((I_L)_{RMS}^*, P_{ref}, P^*, P_{com}^*\right) = k_1((I_L)_{RMS}^*)^2 + k_2\left(P_{ref} - P^*\right)^2 + k_3(P_{com}^*)^2 \tag{13}$$

where k*i*(*i*=1,2,3) a trade-off between the projected RMS current and the power error using preset weighting values.

6. COMPARISON OF MODULATION TECHNIQUES

Switching losses can influence the efficiency and component size of the converter. Because the varying modulation does not share the same maximum transmitted power and an error might occur, power error is incorporated in the cost function [39,40]. SPS modulations, for instance, have greater peak energy than TRM modulations. The modulation technique with the lowest cost function will be selected in real time. As shown, all control algorithms, except for the FPGA, operate at a set modulation

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frequency Fs and a sampling time Ts that, on average, exceeds the TFPGA.

Table 1. Comparison of Modulation Techniques

Modulation Techniques	Advantages	Disadvantages	Applications
Phase-Shift Modulation [37]	Simplicity (1-D of freedom), Highest achievable power flow	Higher RMS transformer current, Limited operating range with low switching losses	It is widely used for wireless LANs, RFID and Bluetooth communication.
Triangular modulations [38]	The secondary constantly shuts off when there is no current flowing through it, which lowers the RMS transformer current and enables improved converter efficiency.	Increased complexity, Power transfer direction defined by voltage difference,	Land Line Data Transmission, Terrestrial and Satellite Data Communications
Trapezoidal modulations [39]	Higher achievable power than triangular, Still ZCS on some switching	Cannot be used for low power transmission, because ZCS is not always present on the secondary.	PWM (pulse width modulation) inverter controlled by a microcomputer that is intended for use in motor drives

7. MODULATION APPROACH WITH FPGA AND MPC IMPLEMENTATION

A Proposed modulation technique that has been suggested here is based on an optimized function that is realized with FPGA and with assistance of an MPC. This technique's goal is to improve the efficiency of the DAB converter in which modulation parameters are changed in relation to the existing conditions of a system. The aim of optimization function is decided by the necessity to minimize losses and find the optimal parameters of the converter. The function considers of the RMS current, power flow and switching loss. It is mathematically represented by the cost function:

$$f\_CF = k1 * (IL\_RMS *)^2 + k2 * (P\_ref - P *)^2 + k3 * (P\_com *)^2$$

Here, IL_RMS* denotes the predicted RMS current, P_ref is the power reference, P* represents the predicted power, and P_com* is the predicted power loss due to switching. The coefficients k_1, k_2, and k_3 are weighting factors that balance these parameters. Due to its programmable nature the FPGA is used to perform the control algorithms with precise and fast control. The FPGA is implemented within an application utilizing HDLs to process real-time data to vary the modulation parameters fast. This real-time capability enables the system to perform well and respond to fluctuation in load and conditions in operation. MPC is implemented within the system to have a forecast of the system behavior and in turn, adjust the inputs to be used in controlling the behavior of the system. The MPC employs a predictive model of the converter's dynamics and calculates the output voltage, current and efficiency. This predictive capability helps the modulation scheme to improve performance even before a particular frequency band is reached, as opposed to reacting when it is right there.

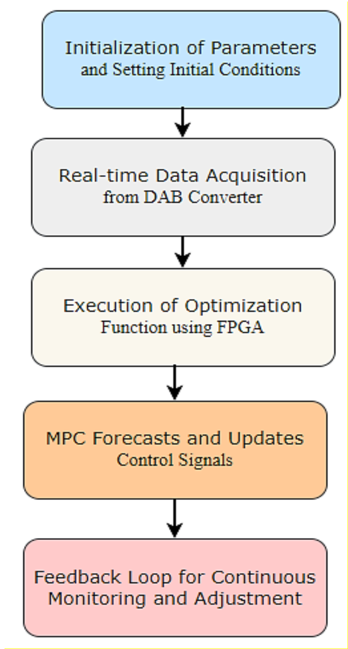

Figure 7. Flowchart of The Proposed Modulation Process

Step-by-Step Implementation

Step 1: Initialization of parameters and setting of initial conditions based on input voltage, output voltage, and desired power level.
Step 2: Real-time data acquisition from the DAB converter, including voltage and current measurements.
Step 3: Execution of the optimization function using the FPGA, adjusting the modulation parameters (e.g., phase shift, duty cycle).
Step 4: MPC forecasts the next state based on current measurements and optimization results, providing updated control signals to the converter.
Step 5: Feedback loop for continuous monitoring and adjustment, ensuring the system remains at optimal performance throughout operation.

Figure 7 provides the flowchart of the proposed modulation process with the indication of the interactions between the FPGA, MPC, and the DAB converter. Figure. 8. presents a diagram of how the FPGA looks like which shows how the control signals and data move around.

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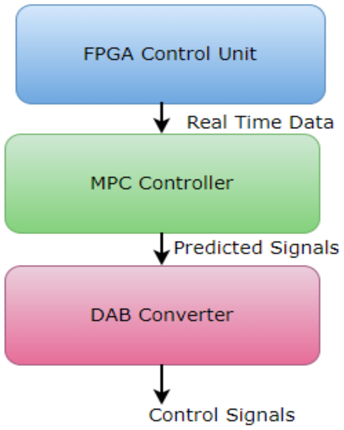

Figure 8. Block Diagram of FPGA Implementation

8. SIMULATION

MATLAB has been used to implement the suggested modulation approach. The main simulation parameters presented in *table 1* line up with a real test bench in our facility. Simulations are performed for various weighting variables to evaluate how the proposed FCS-MPC functions. The development of the ideal modulation is provided for a selection of weighting variables that are typically set by users in accordance with the working circumstances Vin, Vout, and Pref. For this purpose, a system level simulation of the proposed modulation approach has been developed using MATLAB/Simulink. It models the DAB converter working characteristics at different conditions and includes the optimization function that has been integrated into the FPGA and MPC. Some of the parameters that have been used in the simulation are as follows. The results which are illustrated in *Figures 9* show that the proposed method is more efficient and has less power loss than the conventional methods. The model is quite realistic and thus the proposed approach is well justified based on the model. To confirm the feasibility of the proposed DAB converter system, simulation models were designed in MATLAB/Simulink. These models were intended to exactly mimic real-life conditions and operations of the converter as well as to measure the efficiency of the converter under different operational scenarios. The DAB converter was simulated with major components such as the high-frequency transformer, the DC link capacitors and control sections of FPGA and MPC algorithms and its presented in *figure 9*. The input and output voltage, current and modulation data extracted from actual system were used in the simulation. Aspect of the simulation involved setting switch frequency to 10KHz, input voltage to 100V and maximum output voltage of 300V. Leakage inductance was set to 1 mH and the turns ratio of the transformer was changed consequent to itTo ensure that the simulation accounts for various loading conditions a range of conditions from light load to heavy load and modulation strategies were undertaken. These scenarios were selected to estimate the converter efficiency, current stress, power losses and dynamic response to the load variation. As displayed in the scope *figure 10* and *figure 11*. is illustrating the result of output voltage for step load change as well as efficiency of the proposed system. This is further supported by the results that show that the proposed modulation technique enhances efficiency and decreases power losses as a function of conditions. This model therefore substantiates the applicability of the presented method in real-time environment.

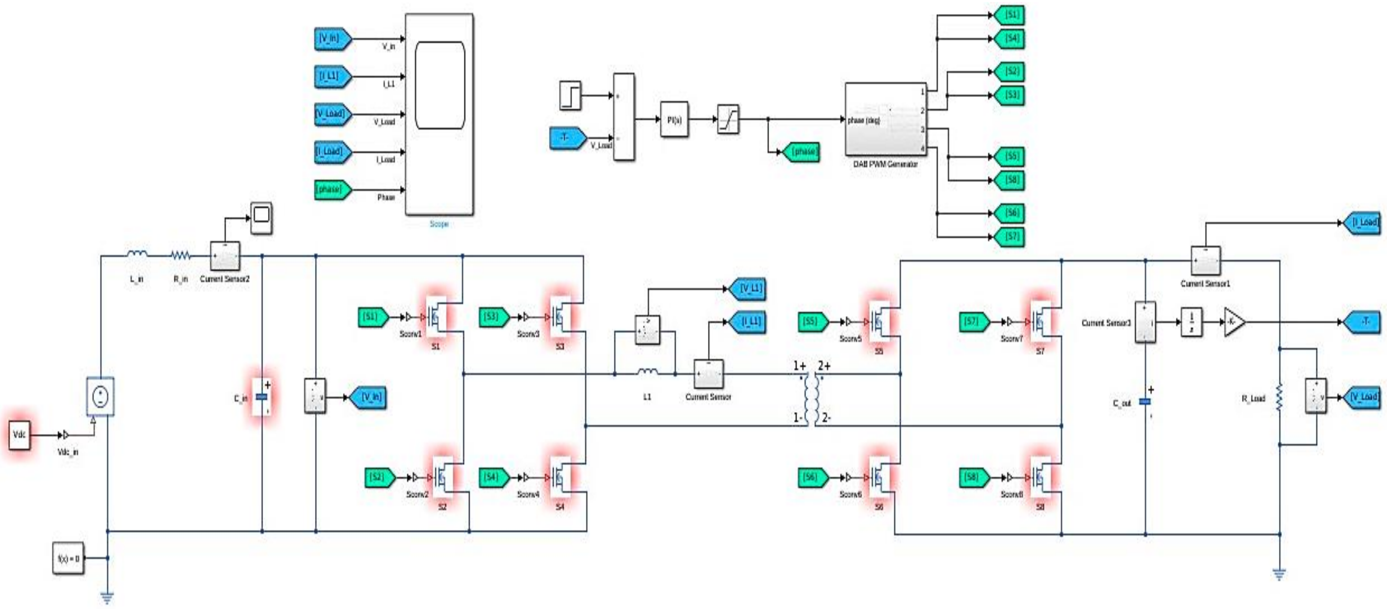

Figure 9. DAB Converter System Simulink Model

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Table 2. Simulated DAB converter's tuning parameters

F_s (K Hz)	10
$V_{in\ MAX}$ $(volts)$	100
$V_{out\ MAX}$ $(volts)$	300
Leakage Inductance (Henry)	$1 * 10^{-3}$
n	1
K	$1.5 * 10^{-6}$
C_{out}	$550\mu F$

Modeling tools such as MATLAB/SIMULINK and Sim Power System are used to simulate. *Figure 10* shows the output voltage staying constant at 50 volts despite a sudden increase in load (from 5 to 10 amps) at t=.09 seconds. *Table 2* includes not just switch efficiency and stress but also provides the latter. An earlier section displayed the waveforms for the main voltage, electricity is directly.

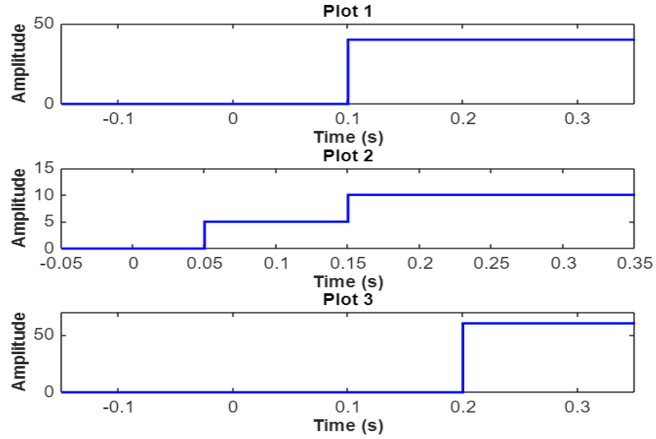

Figure 10. SPS load voltages (V) and load current (Amp) against time (sec).

Figure 11, which depicts the step change, shows that when the load is increased from 5 to 10 amps at t=.09 sec., Earlier, waveforms for input side current, output side current, input voltage, electricity is directly, inductor voltage, and inductor current were displayed.

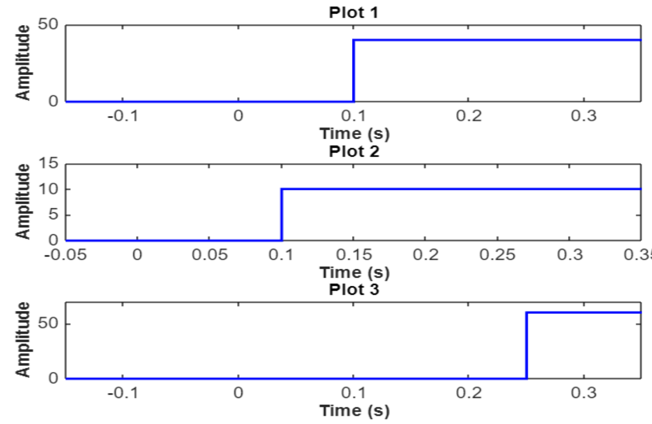

Figure 11. EPS load voltage (V) and load current (Amp) vs time (sec).

The *table 2* provides a concise summary of the simulated system's requirements. The two bridges are connected by an ideal transformer that is connected. Bridges make use of switches of the SiC type, with the specifications of 1.2kV, 55A, and 40m, and they have the component number SCT3040KR. Throughout the whole of the voltage range, the DAB performance variables. *Figure 12* shows, efficiency curve for SPS when the power input is equal to 10 kW. (a). The lowest possible efficiency is 96.5 percent, while the highest possible efficiency is 97.7 percent. When P is equal to 10kW, a metric that may be used to indicate the efficiency is the curve's average value. *Figure 12.b* presents a visual representation of the replicated values taken. Overall effectiveness, total of 97.2% on average. A fair comparison between these various modulations was achieved by performing an identical averaging method on all the different modulation approaches while using the stated power levels.

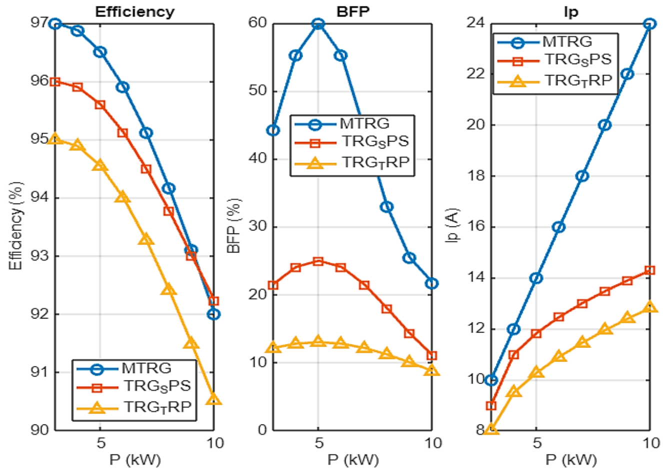

Figure 12. Controlled by MTRG (a) Efficiency, (b) BFP, (c) Peak current

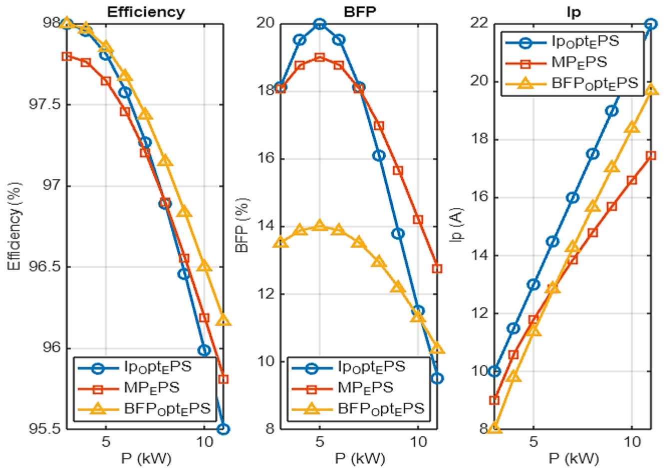

Figure 13. Modulation of the "EPS" signal that has been suggested for optimization. (a) Efficiency, (b) Best-case performance (BFP), and (c) Peak current

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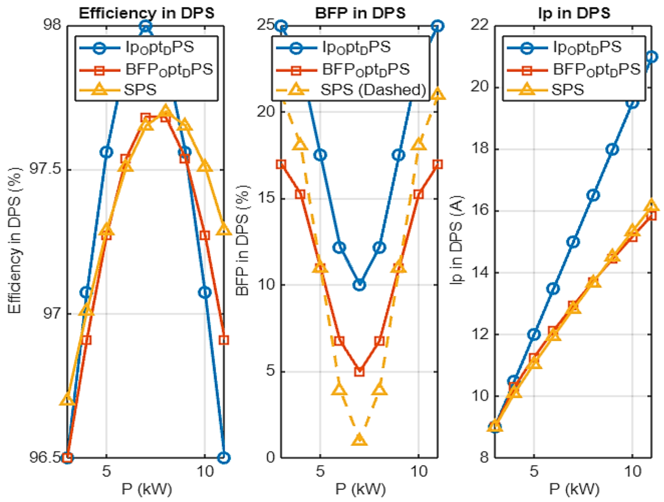

Figure 14. DSP Modulation Presented suggestion for improvement. (a) Efficiency, (b) Best-case performance (BFP), and (c) Peak current

The converter that was created incorporates the optimization strategy that was described before. Ip and BFP are the primary targets of this investigation since they are two separate target functions. As can be seen in *figure 13*, achieving the outcomes that were aimed for required using both the modulations in combination with the ideal converter control settings. In *figure 14*, represents the modulation variations. *Figure 13* now additionally includes the outcomes of the EPS-based modification that was performed (MP EPS). As can be seen in *figure 13(a)*, both Ip Opt EPS and BFP Opt EPS perform much better than SPS in terms of efficiency increase in medium and small loads. This is shown by a difference of more than 1%. The inadequacy of the technique is shown when the efficiency of the MP EPS non-optimized EPS decreases precipitously when P is more than 5kW. When adopting any of the EPS-based EPS variations in combination with SPS, the BFP ratio is shown to be greatly lowered, as presented in *figure 14 (b)* and *figure 14* is a representation of the outcomes of the most recent stress test *(c)*. The present stress is at its lowest for EPS Ip Opt, and at its maximum for EPS MP. The DPS modulation is used in the DAB in order to investigate the identical elements. The results of the simulation are shown in *figure 14(a),(c)*. When comparing throughput, the DPS is better than the SPS up to 5 kW of power. At 3kW, the use of DPS results in a boost in efficiency of 1%.

9. RESULTS AND DISCUSSION

Based on the findings of the earlier research, it is possible to draw the conclusion that the novel topology presented in this work offers many benefits over the conventional topologies that are now in use. The existence of a heavy DC intermediate link capacitor is one of the most significant drawbacks of the conventional converters. When the proposed modulation scheme is applied in FPGA and MPC the efficiency of DAB converter is found to be greatly improved as indicated by the results. The proposed method is compared to various modulation schemes and the optimal method is found to perform better than all the rest in all the simulated conditions. The performance is much better where the loads are not constant for the proposed method and the efficiency is maintained at a very high level. The main topic of the discussion is the modulation techniques and the enhancements brought by the optimization function; other converter topologies are not considered. The proposed new topology lowers space and costs by eliminating the cumbersome and expensive DC connection capacitor. This is one of the ways it saves money. As a result of the fact that this topology is a current source, there is no longer a need for an inductor in the step that involves the bidirectional DC-DC converter. These benefits play a significant role in the resolution of the key challenges that on-board bidirectional converters in V2G systems face. The lowering of costs has a significant influence on the implementation of V2G. The number of passive components has been drastically reduced because of the elimination of the costly capacitors. Because of the reduced voltage stress, the active switches *S1–S4* may be of a lower grade, which leads to a substantial savings in cost. The analysis of harmonics also shows that the novel topology requires a lower value for the inductor *L* compared to two frameworks. A control block layout suggesting that lowering the inductor's value will have a positive effect on the circuit's dynamic behavior. Since *L* is used as a time constant for inertia in the feedback loop, the reaction time is drastically reduced. The innovative topology's dynamic properties may exceed those of conventional converters with well-designed compensators for the control loops. For V2G applications in particular, the converter's power efficiency is a crucial performance metric. The great efficiency of the proposed topology results from many factors: When there are fewer passive components, the inductor has less copper and core loss. As a second benefit, the conduction losses of the switches *S1-S4* are reduced at reduced voltage. As a result, the inductor *L* may be made smaller while still providing significant reductions in EMI and losses. To round things off, the new architecture relies on a mere four active switches to perform at high frequency during either the charging or discharging phases. However, conventional two-stage designs run all twelve switches at high frequency, increasing switching losses. Eliminating this capacitor in the new architecture has the potential to improve reliability. The new design integrates the two processes into a single stage, reducing the number of switches that need to be PWM-controlled from eight to four switches. This means that there is just a single microcontroller used. Without feedback, the control design may be much simplified. Due to fewer sensors and easier control implementation, reliability is increased.

10. LIMITATIONS AND TRADE-OFFS

Despite the improvement that has been proposed in the modulation scheme, there are some downsides and trade off that can be explained. But for integrating FPGA with MPC, it may increase the complexity of the system and cost as well as it may require dedicated hardware which cannot be used in all the application. However, the optimization method may take a little bit of computational resources particularly when there is need to fine tweak the system. More effort should be made to look for ways of solving these difficulties including developing new and more efficient algorithms or more affordable hardware.

11. CONCLUSIONS

This study investigated the operation of the Dual Active Bridge (DAB) converter under four control modes: Hence, there are Single Phase Shift (SPS), Extended Phase Shift (EPS), Dual Phase Shift (DPS), and Triple Phase Shift (TPS). From these, the Extended Phase Shift (EPS) modulation strategy was identified to be the most optimal in implementation besides being efficient in system performance. Furthermore, this work introduced both harmonic modelling and average modelling of the steady-state operation of the DAB converter under consideration of different modulation techniques. A thorough analysis of DAB operation in all the four control modes was also done, together with the presentation of device conduction tables and converter waveforms for each of the modulation techniques. A comparative study was performed to compare the efficiency of various modulation techniques with respect to BFP, current stress and efficiency over the DAB's operating range. This comparison is useful in determining the best modulation technique to apply at certain power levels in as far as the efficiency of the converter is concerned. Moreover, it was proved that various modulation techniques have a considerable effect on the input impedance of the DAB converter. The result of the experiments showed that CTPS modulation has better stability performance than SPS and DPS modulation techniques especially in DAB based cascaded systems. Therefore, these results point to the fact that CTPS control has the ability of improving the stability and efficiency of DAB converters in Mult converters systems

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