Steady state and dynamic performance assessment of high power bi-directional dc-dc converter topology: SMC as control technique

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ABSTRACT
The modern Power Electronic Systems generally require high quality, portable, light weight, reliable and efficient power supplies. The switched mode power supplies (SMPS) technology is developing very rapidly. This bidirectional dc-dc converter has attractive features because of its high efficiency and compact size and is used in various industrial applications. The switching action of converter produces nonlinearities, which affect the overall performance of the converter. Hence there is a need to design an appropriate controller which can handle nonlinear situations and the performance of the converter can be improved. In this paper nonlinear hysteresis modulation based sliding mode controller for said converter is designed. The performance of controller is verified with existing (PI) controller. The results clearly reflects that the designed controller is robust for the converter, has fast response time and reduces overshoot in output voltage as well as in the inductor current as compared with previous research work..

Keywords
Switched mode power supplies, DC-DC converters, Dual-Active Bridge, Hysteresis Modulation Non-linear Controller

1. INTRODUCTION
High frequency dc-dc converters are now days widely used in the diversity of Power Electronic applications. High operating frequencies will cause in reduction in the size of passive components, such as inductors, capacitors and power transformers [1-4]. By operating the converter at higher frequencies the switching loss at both the conditions of turn-on and turn-off increases as the frequency increases beyond the range of 4 kHz [5].
Switching of the converters at high frequencies will affect the power quality because the converters will produce inrush, pulsating current phenomenon with excessive harmonics and high voltage distortion.
Power quality problems usually involve a variation in the electric service frequency voltage or current, such as voltage dips and fluctuations, momentary interruptions, harmonics and oscillatory transients causing failure, or mal-operation of power equipment [6-8].
The dual active bridge converter is believed to have attractive features for high-power applications and the favorable dc-dc converter that is realized is a Dual- Active Bridge in particular when a bi-directional power flow is demanded [8-9].
The analysis and control of dual-active bridge dc-dc converter has been the subject of much research work. Many techniques were used to model the converter focusing on finding the best approach to analyze and control the behavior of the converter.
Many controllers were used to handle the Dual-Active Bridge dc-dc Converter topology and the recent research work though have been done in the proposed area but control strategy design is fraught with some problems and is not giving desired results. Various researchers [4,8, 10-14] have also pointed out that the behavior of the conventional controller is not appropriate during dynamic operation and this is due to an increase of the inductive current resulting in excessive conduction loss and reduction in the efficiency of the converter. This requires that effective control strategy should be developed to get desirable characteristics.
In the past the PI controller was used [7,8, 10-12].The controllers (P, PI) are generally based on linear functions and they often fail to perform satisfactorily under large parameters or load variations and these controllers are also very sensitive to variations of the system parameters. Further, these are optimal at some fixed operating conditions only but their performance may not be optimal under varying operating conditions [7.10.15]. This means that there is a dire need to investigate some advanced strategies for the applications. The sliding mode controller is a non-linear and advanced controller and hence can be readily used to overcome the weaknesses discussed above.
Sliding mode control offers several advantages: stability even for large supply and load variations, robustness, good dynamic response and simple implementation conditions [3, 15-16,]. Moreover, it provides stable frequency in steady state and allowing synchronization to external triggers. Sliding mode controller is therefore considered as a non-linear controller [3,17]. The SMC is nonlinear which is believed to handle uncertainties in the said converter.

2. DUAL ACTIVE BRIDGE DC/DC CONVERTER
The dual active bridge dc-dc converter is bi-directional converter; the active switches are connected at both sides primary as well as at secondary of transformer, as shown in Figure1.

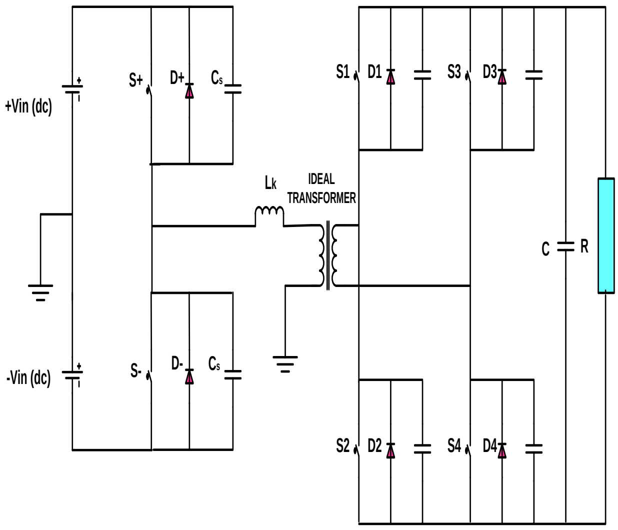

Fig 1: Dual-Active Bridge dc-dc Converter

If the power is transferred from primary side to the secondary of the transformer, then it is called step-up (boost) converter and if power is transferred from secondary to the primary then such converter is called step-down (buck) converter.
The State-Space model of the converter is given below [5]:

$$\begin{bmatrix} \dot{X}_1 \\ \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1-d_1}{L_k} \\ \\ \dfrac{1}{C} & -\dfrac{1}{RC} \end{bmatrix} \begin{bmatrix} X_1 \\ \\ X_2 \end{bmatrix} + \begin{bmatrix} \dfrac{2d-1}{L_k} \\ \\ 0 \end{bmatrix} V_{dc}$$

The above model is of second order system, in which the inductor and capacitor are the state variables of the converter.

3. DESIGN OF SLIDING MODE CONTROLLER (SMC) FOR THE DAB DC-DC CONVERTER

With the extensive development of the sliding mode control theory, its application studies have also progressed radically. This control theory has been successfully applied to various engineering problems and in particular its application is gaining popularity since last two decades towards the switching of the power converters. The SMC method is mainly preferred by power electronics and control engineers because that the parameters of power converters are varied continuously due to their switching conditions, networks and the load, and SMC is very robust against these parameter variations [17].
The sliding mode control design approach consists of two components.
i. To design of a switching function so that the sliding motion satisfies the design specifications.
ii. The selection of a control law, which will make the switching function attractive to the system state.
Converter switches are driven as a function of the instantaneous values of state variables, this will force the system trajectories to stay on a desired surface space called sliding surface. There are many control techniques that are used in sliding mode control. Hysteresis modulation is one of the popular techniques of the sliding mode controller.

3.1 Hysteresis Modulation Technique

Hysteresis Modulation technique of the sliding mode controller is based on the signum function type of Hysteresis switch [16]. This SMC technique is attractive especially for 2^{nd} order converters. The proposed converter is also of 2^{nd} order converter in which two state variables are sensed, the state variables are inductor current and capacitor voltage. It will force the system trajectories to the desired surface i-e sliding surface.

The implementation of this technique does not require auxiliary circuitries and this approach is easily accomplished by introducing a layer of Hysteresis band into the signum function [3,16]. This method is easily accomplished by Eq.(2):

$$u = \begin{cases} 1 = \text{"ON"} & \text{when} \quad S > k \\ \\ 0 = \text{"OFF"} & \text{when} \quad S < -k \end{cases} \qquad .....2$$

From the general Eq. (2) and the phase description of this equation is given in Figure 2, the switch will turn-on when the condition S>K and the switch will off when S<K. The S=K means the constant frequency is controlled with this controller. This controller controls the state variables between two boundaries. It will suppress the higher frequencies and allow the desirable frequencies to maintain the output responses.

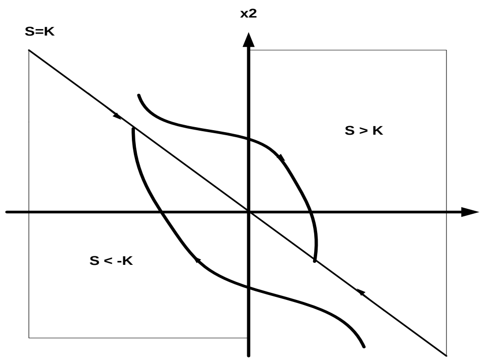

Fig 2: Hysteresis Modulation based Sliding Mode Control

In the designed sliding mode controller the hitting and existing conditions are satisfied which states that the system trajectory must eventually reach the sliding line, as given in the control law of Eq. 2.
Where K is small value of S, that is S = K and S = -K provides a form of control of the switching frequency of the converter
As for as dc-dc converters are concerned the motion rate of the current is faster than the motion rate of the output voltage. Therefore, this problem is solved by using dual-loop control structure which contains two control loops, the outer loop and inner loop.

Figure 3 shows the novel proposed control scheme of SMC for Dual Active Bridge dc-dc converter with cascaded loop structure and the internal structure of the cascaded loop structure is shown in Figure 4.

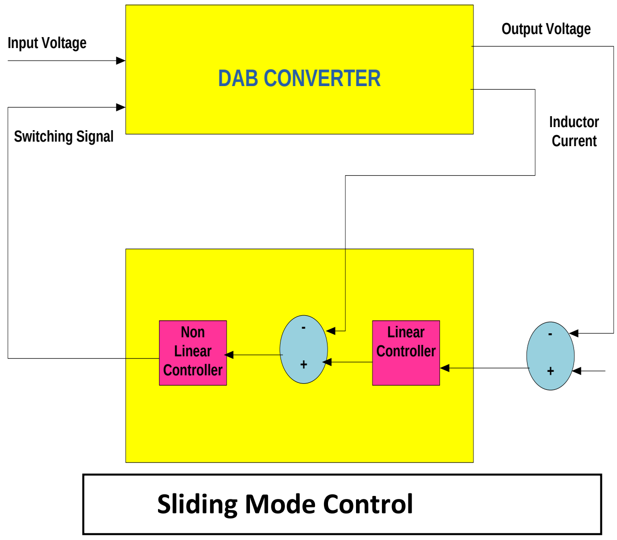

Fig 3: Novel Proposed Control Scheme of SMC for DAB Converter

The designed Sliding Mode Controller consists of two loops (Outer and Inner). The outer loop (Output Voltage) is controlled with PI Controller and inner loop (Current loop) is controlled with Hysteresis Control and the combination of two loops represents as a sliding mode controller. The Hysteresis controller is used to control the non-linear part of the converter that is inductor current.

The design of the current controller depends on the inductor ripple current of the converter. The switch has two states, switch on point and switch off point, in which the controller suppresses the undesirable frequencies. These two states can be calculated from the inductor ripple current of the DAB Converter as discussed [3].

The Hysteresis control is designed on the basis of calculated values of the ripple current as calculated from the above expression. While, the outer loop is controlled with PI and is designed on the basis of linear part parameters. The gain of this controller should be kept low as to decrease steady state error. The integral gain depends on the application in which this scheme is used.

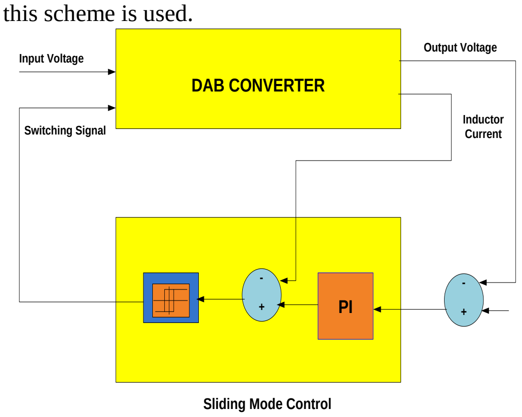

Fig 4: Internal Architecture of SMC Controlled DAB Converter.

4. SIMULATION RESULTS OF DAB CONVERTER

The complete Simulink block diagram of SMC for Dual-Active Bridge is given in Figure 5. The cascaded Control Scheme is used in which the outer (PI) loop controls the output voltage, while the inner loop (HC) controls the inductor current.

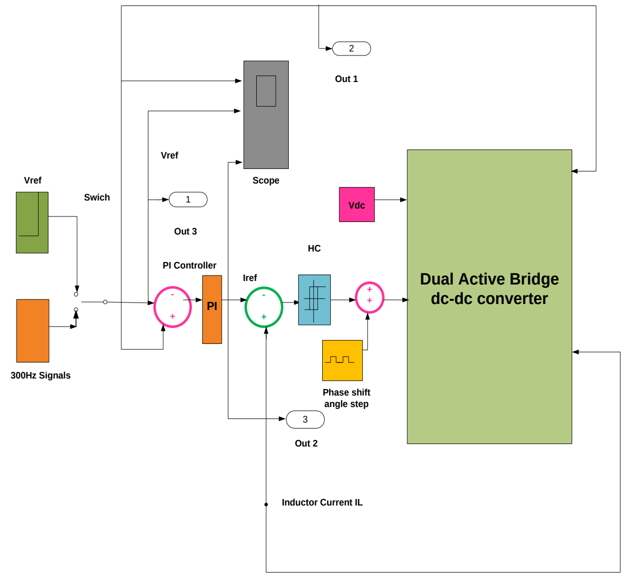

Fig 5: Simulink Block diagram of SMC Controlled DAB DC-DC Converter

4.1 Steady State Operation of DAB Converter.

The simulated results of the converter under steady state operation are given in the Figure 6. The output voltage and inductor current both are free from oscillations. During steady state operation the output voltage is 384 volts and inductor current is 7.68A

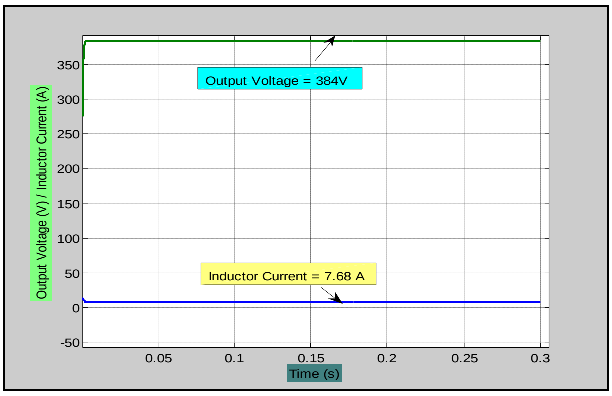

Fig 6: Steady-State operation of DAB Converter

4.2 Dynamic Operation of DAB Converter

The simulation of the DAB converter under dynamic operation is discussed as under:

(i) Line Variations

The line variation performance of the DAB converter is shown in Figure 7 and Figure 8.

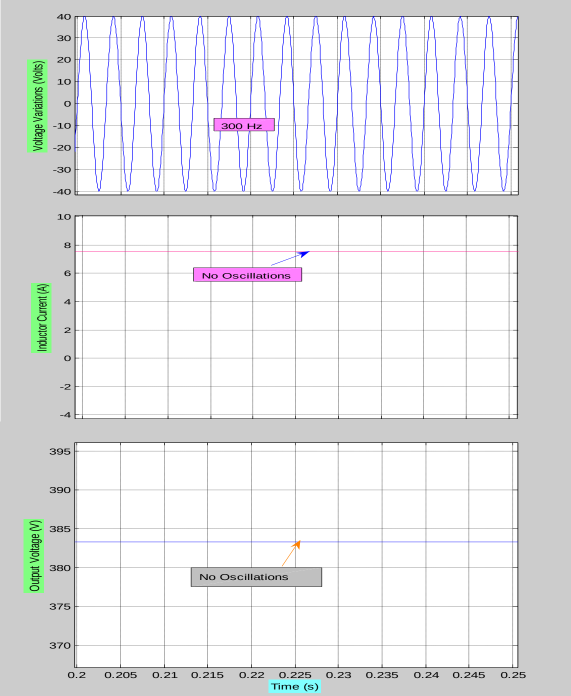

Fig 7: 10% Line Variation

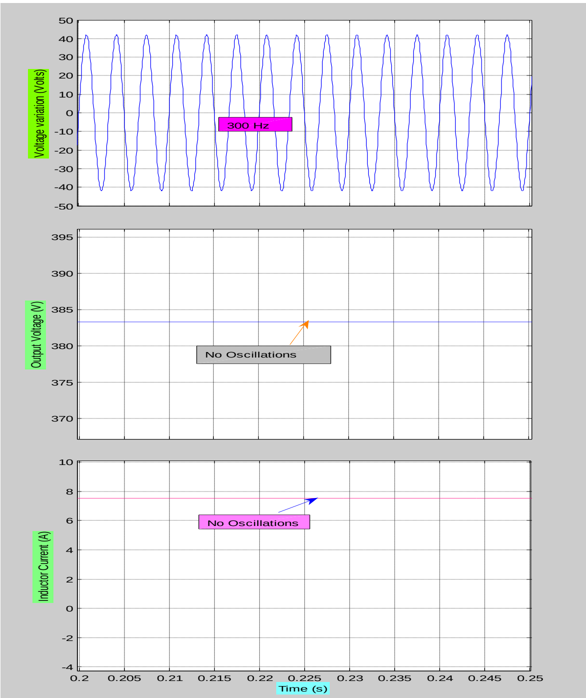

Fig 8: 11.3% Line Variation

The dynamic behavior of DAB converter under line variation is simulated to check the line regulation of the converter. The 10%line variation performance of the converter is shown in Figure 7 and of 11.3% is shown in Figure 8. The frequency of variation is 300Hz because of six pulse diode rectifier is used. It is observed that at both conditions the voltage and current waveforms are free from oscillations. In previous work [13] even at 10% variations in input voltage the oscillations were quite prominent in current and output voltage waveforms.

It is clear that the hysteresis control of Figure 5 with the integral action performing the SMC will force the output voltage and inductor current to stay in a stable condition with a no overshoot in the output voltage as well as in the inductor current.

(ii). Reference Voltage Variations (Dynamic behavior)

The reference voltage variation analysis of the DAB converter is shown in Figure 9.

When step is applied to the reference voltage the output voltage and current increases linearly and when it reaches at the new reference, no production of oscillations are observed at the output voltage and the oscillations as well as the settling time in the current are also reduced as compared to previous research [3,13].

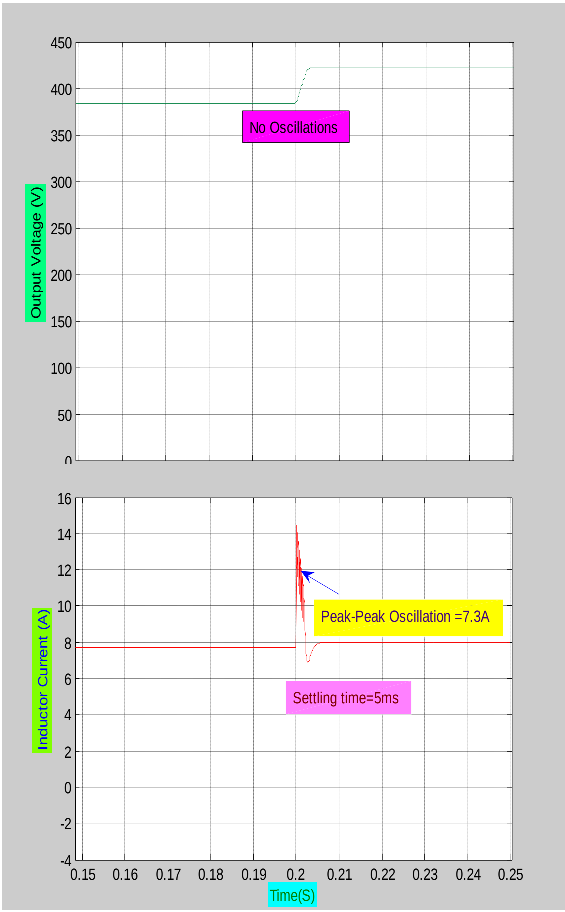

Fig 9: Reference voltage Step Variations Simulation of the DAB Converter

(iii) Phase-Shift Variations (Load Analysis)

The dynamic behavior of the DAB converter can be assessed in Figure 10. This Figure shows the output voltage and inductor current. The controller keeps the output voltage and current at constant level and negligible oscillations have observed in both the output voltage as well in the current. The settling of output voltage and current is 1.25ms.

In previous research work [5,13], the results show the oscillations which are present in the output voltage as well as in the inductor current and the settling tine is 8 times more than that of the present research..

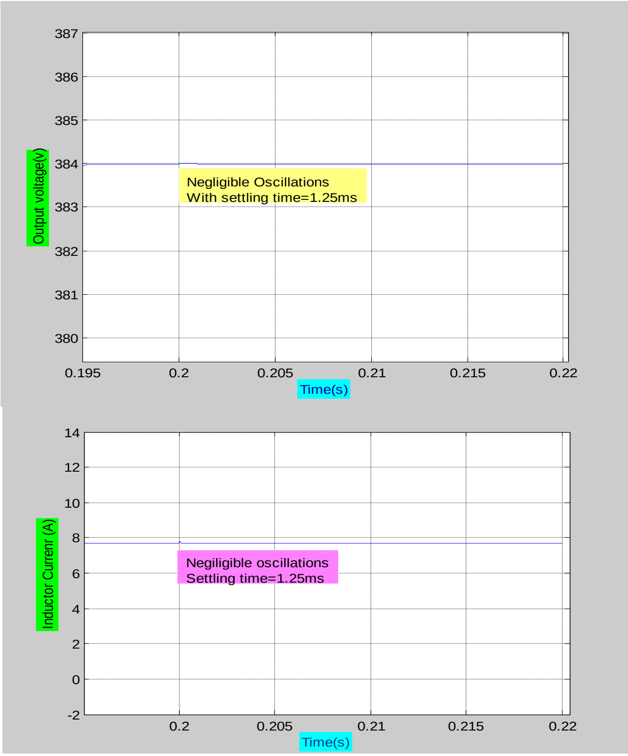

Figure 10 Output voltage and Inductor current of the DAB Converter

5. CONCLUSIONS

In this paper the high frequency dual-active bridge dc-dc converter topology is studied in depth and its serious problems and causes are also analyzed.

The sliding mode controller is designed to handle the nonlinear situations of the above converter which are produced due to the nonlinear behavior of the current. The simulation model of sliding mode controller is designed on the basis of linear and non-linear part. The linear part is controlled by PI controller while the nonlinear part is controlled with Hysteresis control technique.

The performance of the controller is tested under steady-state, line variations, load variations and step change in reference voltage operations. The results obtained under all above situations are much better than the conventional PI controllers [7,13].

The settling time in all cases is decreased from 50% to 80% and the efficiency of the converter is increased as compared to the existing PI linear controller.

With the tremendously improved performance of the DAB converter by using the SMC technique it is deemed that the above controller is being the powerful tool and can ensure the system stability, good dynamic response, and robustness under any nonlinearities.

6. ACKNOWLEDGEMENTS

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