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Battery Energy Storage System Integration to the More Electric Aircraft 270 V DC Power Distribution Bus using Peak Current Controlled Dual Active Bridge Converter

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Abstract— The electrical power requirement of the aircraft has increased due to the secondary loads becoming electrical. This has led to the deployment of high energy density battery (Lithium-based batteries) in the MEA. In this paper, a high energy density battery (lithium–iron phosphate ‘LiFePO4’) is used as the battery energy storage system (BESS). The function of the BESS is to start the engine starter-generator set of the MEA and to provide the transients and emergency loads. The dual active bridge (DAB) dc-dc bidirectional converter is used as the charger circuit for the BESS. The 270 V dc based power distribution network is used in the more electric aircraft (MEA). The BESS is integrated to the MEA 270 V dc power distribution bus using the DAB converter. Since, the BESS has to provide the transients/peak load, the fast dynamic response is required for the DAB converter. The coupling inductor current in the DAB converter is ac and has a peak value. In this paper, a peak current controller is proposed for the integration of the BESS to the MEA 270 V dc power distribution bus. The proposed control provides a limit on the peak current as well as it gives fast transient response. The advantages of using the proposed peak current control on avoiding the saturation of the high frequency transformer core is also reported in the paper. The proposed controller for the DAB converter along with the BESS is designed with respect to the MEA environment and is verified with the simulation results in the PSim simulation environment.

Keywords— *More Electric Aircraft, Bidirectional Isolated DC-DC Converters, Li-Ion Battery, Harmonic Model, Battery Energy Storage System.*

I. INTRODUCTION

Greater emphasis on using technologies which can influence the overall cost as well as fuel consumption has led the designers/engineers to design a more electric aircraft (MEA) replacing conventional devices by electrical systems [1]. On the distribution network side, high voltage direct current (270 V dc bus) based distribution systems is an attractive solutions in comparison to the classical ac distribution systems. The 270 V dc distribution systems offers many advantages such as the overall lower weight etc. [2]. For dc distribution systems,

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Fig. 1. 270 V DC Bus Power Distribution Architecture of a More Electric Aircraft showing the integration of Battery Energy Storage System [3].

the bidirectional dc/ac power inverter connected between the distribution bus and the battery energy storage system (BESS) has to be replaced by a bidirectional dc/dc converter as shown in Fig. 1 [3]. For charging and discharging the battery, the bidirectional power flow and galvanic isolation is required, hence the dual active bridge (DAB) topology is the preferred topology as it offers a bidirectional, isolated, high power density and efficient power conversion. With the integration of the battery energy storage system (BESS) to the main distribution network, a power management strategy can be implemented wherein the generators will supply the load and the BESS will take care of the transient etc. The aforementioned strategy of power management is having a huge potential benefits as it will save the generator from taking extra loads and thus will be efficient in longer run [4].

The MEA consists of many electro hydrostatic and electro-mechanical actuators. In MEA, the conventional hydraulic and mechanical actuators have been replaced as they have the requirement of an increased maintenance and operation cost. During the onset and offset of the electric actuators, a transient is experienced on the distribution bus which can be supplied from the BESS in order to save the generator from taking extra

Fig. 2. Electrical Profile of the DC power required for elevator operated by electrical actuator.

loads. The electric profile for the DC power requirement of the elevator is shown in Fig. 2, which shows that 1.7 kW power is required to operate one elevator electrically. The DAB dc-dc converter must have adequately fast response for the MEA application in order to support the transient/emergency loads as shown in Fig. 2 and also to ensure that the loads do not see any power interruptions. The DAB converter with traditional control strategy like single phase shift control [5], direct estimation of phase shift control scheme [6] etc. may not be able to provide the required transient response. Moreover, the traditional control will make the transformers to saturate on steeply/ rigidly changing the transformer current for large scale change. However, many advanced control schemes requiring two or more degree of freedom (variables) like dual phase shift control [7], triple phase shift control [8], and extended phase shift control [9] have been presented in the literature to improve the dynamic transient response and for efficient and wide range zero voltage switching (ZVS) operation. But, for the MEA applications the above mentioned advanced control techniques may not be suitable as it requires multi degree of freedom (solution of multi variables make the system complex). In [10], the authors have integrated the energy storage system to the MEA network using current controlled DAB dc-dc converter but the above control schemes does not account the algorithm for limiting the peak current of the converter. Hence a simple control technique with fast transient response and with peak current control limited needs to be developed.

In literature, peak current control is a popular mode of control used for pulse-width modulated (PWM) dc-dc power converters such as buck converter [11]. For DAB, the peak current control is used as a mode of control in [12-14], wherein the discussion on its advantages and analysis have been presented. In [12, 14], Dutta et al have implemented predictive phase-shift current-mode control and predictive duty cycle mode of control for the DAB dc-dc converter. A detailed methodology for the prediction algorithm and analysis is reported by the authors in [12, 14] for different cases. A fast response controller was developed owing to the removal of PI compensator in the inner current. With this, the current control loop theoretically has the bandwidth equal to the switching

frequency [13]. However, there still exist a PI compensator in the voltage control loop. In the presented paper, the proposed control strategy is based on the direct estimation/prediction of the duty cycle “d” which is dependent on input and output voltages, output current, transformer current, turns ratio and the switching frequency. The duty cycle “d” is calculated using quadratic solver approach. In the proposed control, the outer loop PI compensator is also removed thus avoiding the issues involved with the PI compensator loop such as the tuning issue with the operating point. Furthermore, in this paper the peak current control technique is proposed for the MEA application as it has an inherent fast dynamic response capability along with putting a limitation on the peak current which eventually increases the battery lifetime. The proposed peak current control will produce symmetrical current (dc offset = 0) on the transformer windings which will avoid the saturation of the transformer core. In this paper, first a BESS is designed for the MEA application and then the DAB converter is modelled and controlled for proper integration of the BESS to the 270 V dc distribution network.

The paper is organized as follows: battery energy storage system (BESS) for MEA is described in section 2. Design and modeling of the charger circuit “DAB dc-dc converter” for the MEA application are presented in section 3. Proposed peak current control for BESS integration to the MEA is presented in section 4. Simulation results are presented and discussed in section 5 and the conclusions are presented in section 6.

II. BATTERY ENERGY STORAGE SYSTEM (BESS) FOR MEA

As discussed in the introduction part, one of the promising power distribution architecture of MEA is a 270 V dc bus system. Hence, for the design of the BESS for MEA, load profile analysis on 270 V dc need to be done. The loads powered by the BESS in MEA for the 270 V dc bus architecture needs to be shortlisted. The BESS has to perform the following functions; (i) to start the engine starter generator (ESG) set, (ii) to boost up the low voltage generation by ESG, i.e. to maintain the 270 V dc bus within the steady-state voltage range (250–280 V) set by the MIL STD-704 F and (iii) to meet the emergency load requirement.

With these load profiles to be supported by the BESS, a LiFePO4 based 50 kW, 6.4 kWh Li-ion batteries are selected for the investigated application [15]. The LiFePO4 battery is selected as safety is the most important parameter while deciding on the type of lithium-ion battery to install in an aircraft. In the presented work, the battery model based on a modified Shepherd curve fitting model is studied and used. The main equations [16] used in modeling of the battery are given in Eqn. (1) – Eqn. (4).

$$V_{batt} = E_o - K \frac{Q}{Q-it} \cdot it - R_b \cdot I - A_b \cdot \exp(-B \cdot it) - K \frac{Q}{Q-it} \cdot i^* \quad (1)$$

$$R_{pol} = K \frac{Q}{it - 0.1Q} \quad (2)$$

$$E = E_o - K \frac{Q}{Q-it} \cdot it + A_b \cdot \exp(-B \cdot it) - R_{pol} \cdot i^* \quad (3)$$

$$R_{pol.} = K \frac{Q}{Q - it} (1 - u(t)) + K \frac{Q}{it - 0.1Q} u(t), \quad (4)$$

where E_0 is expressed in volts as it is the battery constant voltage and K is expressed in volts per ampere-hour as is the polarization constant.

III. DESIGN AND MODELING OF THE CHARGER CIRCUIT “DAB DC-DC CONVERTER” FOR THE MEA APPLICATION

The maximum power transfer, output and input voltages are the main specifications deciding the characteristics of the DAB dc-dc converter shown in fig. (3). The duty cycle (d) and coupling inductor (L_s) design is presented here keeping in view the maximum power transfer and wide range operation of ZVS for the converter. Fig. (4) shows the dependence of coupling inductance (L_s) on the “duty cycle, d ” and “output power, P_o ”. Eqn. 5 and eqn. 6 respectively shows the two instant (I_{pk} and I_r) of the inductor current (i_L) given in fig. (5). Solving eqn. (5) and eqn. (6), the power transfer equation can be derived and is given in eqn. (7). Eqn. (8) governs the dependence of coupling inductance (L_s) on the “ d ” and “ P_o ”.

$$I_{pk} = [V_o(2d - 1) + nV_{in}] \frac{T_s}{4L_s} \quad (5)$$

$$I_r = [nV_{in}(2d - 1) + V_o] \frac{T_s}{4L_s} \quad (6)$$

$$P_{transfer} = \frac{nV_m V_o (d - d^2)}{2L_s f_s} ; \quad P_{norm.} = (d - d^2) \quad (7)$$

$$L_s = \frac{nV_{in}(d - d^2)}{2I_o f_s} \quad (8)$$

IV. PROPOSED PEAK CURRENT CONTROL FOR BESS INTEGRATION TO THE MEA

The proposed control structure for peak current control of DAB dc-dc converter is shown in fig. (6). The key operating waveform of the DAB dc-dc converter is shown in fig. (5). As seen from the fig. (5), the inductor current has two values of I_r in a cycle i.e. this current instant occurs twice in every cycle thus making the proposed control to operate on cycle by cycle basis. This cycle by cycle operation makes the controller to respond for any changes in the reference command within a cycle thus making it a fast response controller. The peak current based control scheme is in use for the fundamental dc/dc converter like buck converter [17]. In buck converter, the peak current control is used for the generation of the switching command for the main switch. The peak current control of the buck converter is different from the DAB dc/dc converter as the inductor current in the buck converter rises and fall with two slopes rate whereas in the DAB dc/dc converter it rises and falls with four slope rates. The dual loop controller is used here wherein the outer loop generates the reference for the peak current whereas the inner loop generates the switching command on comparison with the actual inductor peak current. From fig. (6), first the output voltage and current is sensed to determine the value of “ d ”. The predefined value of “ d ” is

calculated using eqn. (7). This “ d ” is further used in eqn. (6) to calculate the predefined “ I_r ”. This “ I_r ” is the reference peak

Fig. 3. Schematic of DAB dc-dc converter.

Fig. 4. Effect of output power and duty cycle on the coupling inductance [3].

Fig. 5. Key operating waveforms of DAB dc-dc converter.

current which is compared with the actual inductor current to generate the switching commands/signals for the secondary bridge. As seen from figs. (5) and (6), the primary bridge is supplied (driven) by a fixed 50 % duty ratio signal whereas the secondary bridge is also driven by the fixed 50 % duty ratio signal but with a phase shift. The phase shift value is dependent on the time duration required for the “ i_L ” (inductor current) to reach the predefined specified reference value (I_r) also known as the peak current of the inductor. The switching logic for the secondary side switches are given in Table 1. Thus, the

Fig. 6. Proposed control structure for peak current control of DAB dc-dc converter.

Table 1: Switch Logic for the secondary side switches {S₅, S₆ forms one leg and S₇, S₈ forms another leg as seen in fig. (1)}

Conditions	Time	S	R	Q	Switch State
Case 1	t ₁ – t ₂	I _{r,act} > I _{r,ref} ; S = 1	I _{r,act} > - I _{r,ref} ; R = 0	Q = 1	S ₅ and S ₈ will be ON; S ₆ and S ₇ will be Off
Case 2	t ₂ – t ₃	I _{r,act} < I _{r,ref} ; S = 0	I _{r,act} > - I _{r,ref} ; R = 0	Q = 1	S ₅ and S ₈ will be ON; S ₆ and S ₇ will be Off
Case 3	t ₃ – t ₄	I _{r,act} < I _{r,ref} ; S = 0	I _{r,act} < - I _{r,ref} ; R = 1	Q = 0	S ₆ and S ₇ will be ON; S ₅ and S ₈ will be Off
Case 4	t ₄ – t ₅	I _{r,act} < I _{r,ref} ; S = 0	I _{r,act} > - I _{r,ref} ; R = 0	Q = 0	S ₆ and S ₇ will be ON; S ₅ and S ₈ will be Off

proposed peak current control works on the principle of the predictive phase shift peak current control wherein the peak current is predicted to calculate the phase shift required for exact power transfer to supply the loads. Since the BESS is supplying different loads in the system such as ESG, emergency backup power, transients loading etc., then the control variable will be output voltage as the peak current adaptively changes with the load fluctuations. Hence, in the simulation results, output voltage is shown to be regulated in different scenario with the proposed control scheme.

The proposed control is different from the conventional dual loop controller, as in the conventional dual loop control a PI controller is required for mapping the outer loop control function to the inner loop control function. In the proposed control, PI control action is not required as the prediction of the peak current is done to determine the switching instant. With the use of the proposed control, two major drawbacks for the PI controller which can be eliminated are: (i) PI controller slows down the dynamic response due to the integral action and (ii) the PI coefficients are tuned for a particular operating conditions. The other advantages associated with the peak current control are that the efficiency of the converter will be higher as limiting the peak current will reduce the switching loss of the switches and the core loss also will be reduced since both of these losses are dependent on the peak current.

V. SIMULATION RESULTS AND DISCUSSION

To verify the control structure shown in fig. (6), the simulation is performed in PSIM 9.3 software. The simulation operating condition is given in table 2, whereas the system test condition is given in table 3. The performance of the proposed peak current control structure is compared with the conventional

Table 2: The operating conditions for simulation

Simulation Set up Parameters	Rating
HV power distribution DC bus	270 V
LV battery storage system voltage	128 V
Battery capacity	50 Ah
Maximum output power	50 kW
Switching frequency	20 kHz
Transformer turns ratio (1:n)	1:2
Coupling inductance (L _s)	8.64 μH
DC bus Capacitor	1 mF
HV side IGBT (Semikron Superfast IGBT Modules)	SKM 300GB063D
LV side IGBT (Semikron Superfast IGBT Modules)	SKM 300GB063D

Table 3: The system test conditions

Conditions	Variation description
Case 1 (0.25 s)	Load demand change from 50 kW to 25 kW
Case 2 (0.50 s)	Load demand change from 25 kW to 25 kW

dual loop control involving a PI controller and the results are captured and presented here. Fig. 7 shows the response of the conventional dual loop controller wherein the output voltage and inductor current are shown. The output voltage shows a high impulse response at the load change point at 0.25s and 0.50s. The output voltage is regulated after many cycles as observed from the transient situation shown for inductor current in fig. (7). In fig. (8), the output voltage and the inductor current response for the step change in load is shown for the case of the proposed

Fig. 7. Conventional PI-based control step-response in output voltage and inductor current.

Fig. 8. Peak current control step-response in output voltage and inductor current.

peak current control. The output voltage is regulated within a cycle as is evident from the waveform of the inductor current shown in fig. (8). Moreover, it is also observed that the average current (dc offset) of the coupling inductor (transformer secondary winding) for the peak current control case is approx. zero (-0.1 A), whereas for the conventional control it is 1.02 A as seen from fig. (7) and fig. (8) respectively. Since the average

current is zero in the peak current control case, there will be zero dc offset in the transformer windings and the dc magnetization will be eliminated thus avoiding the saturation of the transformer core.

VI. CONCLUSIONS

In this paper, the peak current controller of the DAB converter for MEA application has been proposed. The controller has been implemented in the PSIM software based simulation and the comparative results has been shown wherein a better transient response with peak current limited to the predefined value is observed for the case of peak current control. As the proposed control offers a fast response, hence it is suitable for the MEA application as presented in the paper. It has also been found out that with the peak current control technique the DC offset current is zero which will avoid the transformer from saturation. Experimental validation of the discussed peak current control will be done on the hardware setup in the future.

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