

Design and Simulation of isolated converter for Auxiliary Power Module

[Omkar A. Acharya, V.N. Pande]

Abstract— Electric vehicles (EVs) use an Auxiliary Power Module (APM) as a replacement for the alternator in conventional internal combustion engine vehicles. APM takes input power from high voltage (HV) battery and provides output power to charge low voltage (LV) battery and drive the auxiliary loads. For the APM with high input voltage galvanic isolation is a requirement. Soft-switched topologies offer better efficiency and EMI performance. This paper presents selection of suitable topology for such an APM operating within an input voltage range of 82.5 V to 126 V. The design procedure and mathematical computation are likewise incorporated. The designed converter has efficiency of 94%.

Keywords—Auxiliary Power Module, LLC resonant converter, soft switching.

I. Introduction

One of the most viable and sustainable solutions to lower petroleum-based fuel usage and, consequently, lower vehicle emissions is transportation electrification. An Auxiliary Power Module (APM), which is used in place of the alternator in conventional internal combustion engine vehicles, is used in electric vehicles (EVs). APM is responsible for providing power to auxiliary loads driven on 12V like lighting system, speakers, dashboard, etc. Typical architecture of the electric vehicle is as shown in Fig.1. As shown in architecture, APM takes input power from high voltage (HV) battery and provides output power to charge low voltage (LV) battery and drive the auxiliary loads

Higher the voltage of HV battery, lesser the current is required to satisfy the same power output. Lesser current implies lesser heating, lighter weight cables, and thinner gauge electrical conductors that now become less prone to overheating. The overall efficiency of the vehicle is improved with mass savings, meaning even faster accelerations times. Hence it is expected that higher battery voltages will be the norm in the future. Considering above development, this paper discusses feasible topology for an APM suitable for electric performance-two-wheelers and three-wheelers with nominal input voltage as 108V and its design. Following are some important points to be considered for an APM:

1. Galvanic isolation: In the automotive domain, “high-voltage” refers to voltages above 60 V DC. Whenever the voltage level is equal to or greater than 60 V DC, contact protection or in other words galvanic isolation becomes mandatory. Moreover, the ground for the LV side is generally connected to the chassis of the vehicle, as a result the galvanic

between the LV side and HV side is required for human safety, as well as for protection of the LV system.

2. The variation in input voltage to the converter is one of the design challenges for APM.

3. Efficiency of APM is another important feature as it affects the range of the vehicle.

Section II discusses topological evaluation for APM. Section III presents the design of the LLC half bridge. The operation of the topology is well described in literature and will not be discussed in this paper. Section IV presents the simulation results validating the calculated values from the previous section and conclusions are discussed in the last section.

II. Topological evaluation

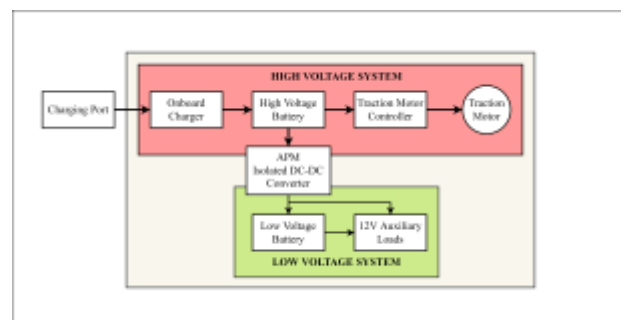


Fig.1. Typical architecture of electric vehicle

For realization of APM, various buck derived topologies like half-bridge, push-pull, forward, full-bridge may be considered. Possibility of soft switching leads to better efficiency and better electro-magnetic interference (EMI) performance. Among forward converter topologies active-clamp forward achieves zero-volt switching (ZVS) for the switches. However, due to asymmetric nature of the topology i.e., current and voltage stresses on the components are distributed unevenly, individual rectifier and switch stresses are higher as compared to full-bridge converters and symmetric half-bridge [1]. Generally, control schemes for half-bridge are symmetric duty cycle control and asymmetric duty cycle control. Symmetric half-bridge is a hard-switched topology whereas in asymmetric half-bridge, ZVS is achieved for both the switches. However, because of the uneven duty cycle distribution for both the switches, asymmetric stresses may be distributed on the associated components. In other words, current and voltage stresses on secondary-side rectifiers are unequal, and current stresses in both the switches are not the same. Therefore, higher voltage-rated diodes are required at the expense of the rectifier stage's performance and efficiency [2]. Recently modified pulse width modulation scheme has been proposed to achieve ZVS operation for either one of the 2 switches without resulting the disadvantages resulting from asymmetric nature in the

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asymmetric control and without the need for additional components [3]. Among resonant topologies, LLC half-bridge is a most attractive resonant topology based on frequency modulation in which ZVS is achieved for both the switches and stresses are also symmetric in nature [4]. The benefits of LLC topology are narrow range of variable switching frequency, wide operating range without affecting normal operation efficiency and ability to achieve soft switching at all loading conditions by utilizing transformer magnetizing inductor [5],[6]. Unlike half-bridge topologies which uses two-switches, full-bridge topologies use four switches. Among full-bridge topologies phase-shifted full-bridge has higher efficiency as compared to conventional full- bridge on account of ZVS operation of all the four switches. Advantage of LLC half-bridge over phase-shifted full bridge is the fact that ZVS is achieved even at no load condition [7]. Moreover, due to absence of output inductor in LLC topology, a single magnetic structure integrating all inductors can be used to save cost and area. When all a circuit's inductive elements are placed in the single structure, electromagnetic compatibility is better. Hence, as LLC half-bridge is power as well as cost efficient topology it is considered as suitable topology for the realizing the dc-dc converter for given APM application. LLC half-bridge for such an application has not been discussed in the literature [8].

Design specifications considered are as follows:

Table 1. Design Specifications

Sr. No.	Parameter	Unit	Values		
			Min	Nominal	Max
1	Input Voltage	Volt	82.5	108	126
2	Output Voltage	Volt	14.2	14.4	14.6
3	Output Current	A	30		
4	Switching frequency	kHz	100		
5	Efficiency	%	93		

III. Design of LLC Half-Bridge

The schematic of LLC Half Bridge topology is as shown in the Fig. 1. The calculations have been made using first harmonic approximation (FHA) which is a popular way for design of LLC Half bridge topology [9]. Steps involved in the calculation are as follows:

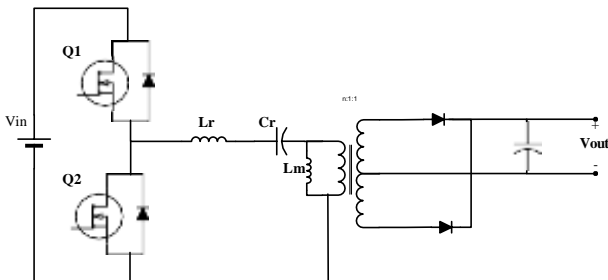


Fig.2. Schematic of LLC Half-Bridge Topology

1.Determine transformer turns ratio:

$$n = \frac{V_{in}}{2V_o} = 3.75 \quad \blacklozenge 4 \quad (1)$$

2.Determine M_{gg_min} and M_{gg_max} :

$$M_{gg_min} = \frac{n * (V_{o_min} + V_{ff})}{2V_{in_max}} = 0.946 \quad (2)$$

$$M_{gg_max} = \frac{n * (V_{o_max} + V_{ff} + V_{loss})}{2V_{in_min}} \quad (3)$$

$$= 1.555$$

$$V_{loss} = \frac{432}{0.93} * 7\% = 1.084 V$$

Here, $V_{loss} = 1.084 V$ is considered as the drop in voltage due to power losses. As the efficiency is considered to be 93%, then 7% of the total power would result in power losses. If all losses are reflected to the output voltage side, then 7% loss at 30 A would reduce the output voltage by 1.084 V. This is added to M_{gg_max} for maintaining voltage-load regulation. To have operation inside the inductive region along with an overload-current capability of 110%, M_{gg_max} is to be considered equal to $1.555 \times 110\% = 1.710$.

3.Select L_n and Q_e :

Gain-curve plots are be created in advance to show attainable peak gain (M_{gg_ap}) with different values of L_n and Q_e . Then L_n and Q_e can be selected to achieve,

$$M_{gg_ap} > M_{gg_max}$$

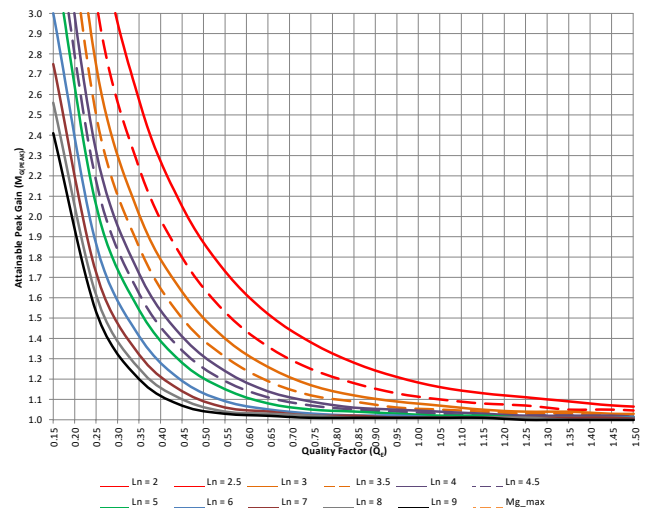


Fig.3. M_{gg} vs Q_e with respect to L_n

From Fig. 3, if the values $L_n = 4.2$ and $Q_e = 0.3$ are selected, the corresponding $M_{gg_peak} \blacklozenge 1.85$, which is greater

than gain required at overload-current capability of 110% i.e., 1.710. A curve for $L_n = 4.2$ is shown in the Fig. 4, it can be obtained by interpolating the curves of $L_n = 4.5$ and $L_n = 5$.

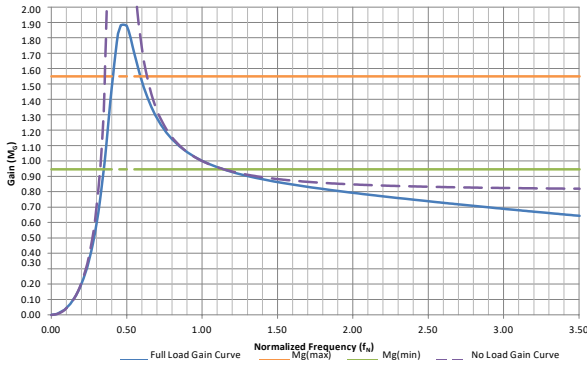


Fig.4. LLC Gain curve with selected and Q_e

The gain curve for the selected values of L_n and Q_e is as shown in the Fig. 4. From the Fig. 4, it can be clearly seen that minimum and maximum gain requirements are satisfied.

4. Equivalent Load Resistance (R_e) :

At full load,

$$R_e = \frac{8 * n^2}{\pi^2} * \frac{1}{I_o} = 6.22 \Omega \quad (4)$$

At 110% load,

$$R_e = \frac{8 * 4^2}{\pi^2} * \frac{V_o}{I_o * 110\%} \diamond 5.7 \Omega$$

5. Design Resonant Circuit's Parameters:

Initially a switching frequency of 100 kHz is selected as the series resonant frequency, and subsequently the parameters for resonant circuit are determined at full load condition:

$$C_r = \frac{1}{2\pi * f_s * R_e} = 0.852 \mu F \quad (5)$$

$$L_r = \frac{1}{(2\pi * f_s)^2 * C_r} = 2.97 \diamond 3 \mu H \quad (6)$$

$$= * L_r = 14.01 \diamond 14 \mu H \quad (7)$$

6. Verify the Resonant-Circuit Design:

1. Series resonant frequency:

$$f_s = \frac{1}{2\pi * \sqrt{L_r * C_r}} = 99.549 \diamond 99.55 \text{ kHz} \quad (8)$$

2. Inductance ratio:

$$L_n = \frac{L_r}{L_r} = 4.666 \diamond 4.67 \quad (9)$$

3. Quality factor at full load:

$$Q_e = \frac{\sqrt{\frac{L_r}{C_r}}}{R_e} = 0.301 \quad (10)$$

Quality factor at 110% load:

$$Q_e = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{e@110\% \text{ load}}} = 0.33$$

Thus, from the Fig.4 it can be clearly seen that at full load the design meets the requirements of:

1. $M_{g@min} = 0.946 @ f_{n,max} = 1.15$ i.e.,
 $f_{n-} = 1.15 * 99.55 = 114.48 \text{ kHz}$.
2. $M_{g@max} = 1.555 @ f_{n,min} = 0.60$ i.e.,
 $f_{n+} = 0.60 * 99.55 = 59.73 \text{ kHz}$.

IV. Results and Discussion

Simulation results are as shown below. Output is regulated for variations in the input voltage. Output voltage ripple is than 200mV. Efficiency of the converter is 94%, which satisfies the requirement.

Fig.5. Output waveforms

Zero voltage switching waveforms are shown in the Fig. 4. ZVS is achieved irrespective of the loading conditions and hence efficiency is maintained at all loading conditions. Soft switching improves efficiency and EMI performance.

Fig.6. ZVS Waveforms

v. Conclusion

Design procedure and the mathematical computation for the LLC Half Bridge resonant converter is elaborated. The designed converter achieves efficiency of 94%. Efficiency can be further improved by replacing diode rectifier with synchronous rectification.

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