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A Novel Three-Port Converter for the On-Board Charger of Electric Vehicles

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ABSTRACT

This paper presents a novel three-port converter for the On-Board Charger of Electric Vehicles by using an impedance control network. The proposed concept is suitable for charging a main battery and an auxiliary battery of an electric vehicle at the same time due to its power handling capability of the converter without additional switches. The power flow is managed by the phase angle (Θ) between the ports whereas voltage at each port is controlled by the asymmetric duty cycle and the phase shift (Φ) between the inverter lags controlled by the impedance control network. The proposed system has a capability of achieving zero voltage switching (ZVS) and zero current switching (ZCS) at all the switches over the wide range of input voltage, output voltage and output power. The feasibility of the proposed system is verified by the PSIM simulation.

Index Terms – Asymmetrical duty cycle control, Phase shift, impedance control network, Bidirectional converter, and 3-port system

1. Introduction

Rapid increase of transportation causes an air pollution thereby accelerating the vehicle electrification. Since electrical vehicles (EVs) have a high potential to reduce the emission of greenhouse gasses and gasoline usage, in near future they are expected to be used all around the world as a clean transportation system. In this circumstance the power grid will play a role to charge the high capacity battery pack in the EVs.

Several papers have been published on an idea of the multiport converter to achieve grid integration and power flow control for different types of multi-input sources. The benefit of multiport converters are 1) a small number of components; 2) quick dynamic response; 3) high system efficiency and power capability, and 4) centralized control.

Conventional converters usually do not achieve very high efficiencies due to the switching losses. To obtain peak efficiencies, high power density converters must operate using soft-switching techniques—zero-voltage switching (ZVS) and/or zero-current switching (ZCS)—to reduce the switching losses. Unfortunately, however, while the conventional converter usually can achieve soft switching under specific operating conditions, it is hard to preserve it (e.g., ZVS/ZCS switching and minimum conduction current) as the power is reduced from the maximum and as the input voltage varies from nominal.

In this paper, a new three-port converter for the On-Board Charger of EVs by using an impedance control network (ICN) is introduced. The proposed concept is suitable for charging a main battery and an auxiliary battery of an electric vehicle at the same time without any additional switches due to its power handling capability of the converter. The power flow is managed by the phase angle (Θ) between the ports whereas voltage at each port is controlled by the asymmetric duty cycle and the phase shift (Φ) between the inverter lags controlled by the impedance control network. The proposed system has a capability of achieving zero voltage switching (ZVS) and zero current switching (ZCS) at all the switches over the wide range of input voltage, output voltage and output power. The feasibility of the proposed system is verified by the PSIM simulation.

2. Analysis of the proposed converter

The circuit diagram of proposed converter is shown in Fig.2, it consists of 3-ports i.e. DC source port (P1), Auxiliary battery (P2) and Main Battery (P3).

To make the analysis simpler only two ports are considered to find the parameters i.e turns ratio, resonant component values and etc.

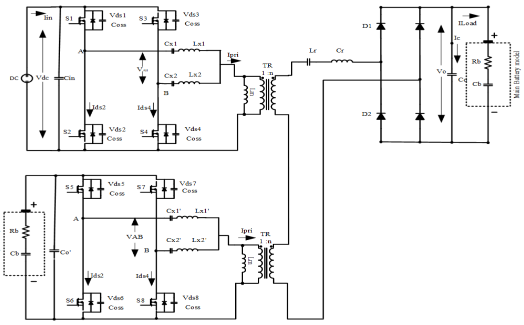

Fig. 1 Proposed Three-Port Converter for the On-Board Charger of EVs

$$\Phi = 2\cos^{-1}\left(\frac{NV_{IN}}{V_{out}}\right) \qquad (1)$$

Here V_{IN} is the input voltage, V_{OUT} is the output voltage, Φ is the phase shift between the two inverter legs and N is the transformer turns ratio. Hence from (1) we can conclude that it is possible to make the admittance seen from the inverter side purely conductive by varying input voltage, output voltages or phase shift. The transformer turns ratio N can be rewritten as (2).

$$N = \frac{V_{OUT,\min}}{\sqrt{V_{IN,\min}^2 + V_{IN,\max}^2}} \qquad (2)$$

The reactance **X** of the impedance control network can be represented as (3).

$$X = \frac{4V_{IN\ \min}\sqrt{V_{out\ \min}{}^2 - N^2 V_{IN\ \min}^2}}{\pi^2 N P_{OUT\ \max}} \qquad (3)$$

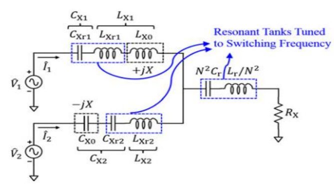

Fig. 2 Equivalent model of 2-ports only

For the easier calculation of reactive components values, it is helpful to split L_{X1} into two series inductors L_{X0} and L_{Xr1}; and split C_{X2} into two series capacitors C_{X0} and C_{Xr2}. With this division, L_{X0} of the top tank can provide the +jX reactance and L_{Xr1} together with C_{X1} forms a filter that rejects the higher order harmonics. In the bottom tank, C_{X0} can provide the -jX reactance, and L_{X2}-C_{Xr2} forms a filter. Fig. 2 shows the model of the ICN converter under fundamental frequency approximation.

$$C_{X0} = \frac{1}{X\omega_s} \qquad L_{Xr1} = \frac{Z_{0X1}}{\omega_s}, L_{Xr2} = \frac{Z_{0X2}}{\omega_s}, L_r = N^2\frac{Z_{0r}}{\omega_s}$$

$$C_{X0} = \frac{1}{X\omega_s}, \qquad C_{Xr1} = \frac{1}{Z_{0X1}\omega_s}, C_{Xr2} = \frac{1}{Z_{0X2}\omega_s}, C_r = \frac{1}{N^2 Z_{0r}\omega_s},$$

Where, ω_s is the angular switching frequency of the converter.

2-1 Asymmetrical duty cycle and phase shift control

For two-source configuration, the power at each port can be expressed as (4)-(6).

$$P_{11} = \left|\frac{(V_1)}{(Z_{or})}\right|^2 R_i \qquad (4)$$

$$P_{12} = \frac{V_1 V_2 \sin(\pi D_1)\sin(\pi D_2)}{\left(1 - \frac{1}{\omega_s^2}\right)|Z_{or}|} \qquad (5)$$

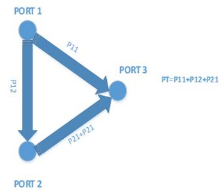

Fig. 3 Power Flow diagram

$$P_{22} = \frac{|V_2|^2}{|Z_{or}|^2} R_i \qquad (6)$$

$$\theta_n = \tan^{-1}\left[\frac{\sin(2\pi D_n)}{1 - \cos(2\pi D_n)}\right] = \frac{\pi}{2} - \pi D_n \qquad (7)$$

Where, D_n is the duty cycle of Port P_n For n=1, 2.

By changing the phase shift θ and duty ratio D in each port the output power and its flow between sources can be controlled. From Fig 3 power flow can be arranged in two ways. One way is that the main source supplies the power to the load and the other way is that the main source supplies the power to both the output load and the auxiliary source by controlling the phase shift and the duty cycle ratio.

Table 1 Specification of the proposed 3-port system

Port 1 DC Voltage	V_1	400 V
Main battery power	P_3	6.6kW
Auxilary battery power	P_2	1.6kW
Main battery Voltage	V_3	250V-420V
Auxilary battery Voltage	V_2	25V-36V

Table 2 Component values

Component	Values	Component	Values
C_{x1}	283nF	C_{x1}'	13.5nF
L_{x1}	12.2uH	L_{x1}'	51.64nH
C_{x2}	220nF	C_{x2}'	1.96uF
C_r	10nF	L_r	252uH
1 n1	1:1	1 n2	1:5.3

3. PSIM Simulation Results

The specification of the proposed system is given in Table 1 and the component values are given in Table 2, respectively. The simulation results by PSIM software are shown in Fig4, 5, 6, 7 and Fig 8. Fig 4 shows the current and voltage waveform of the inverter switches and it is clearly shown that the ZVS and nearly ZCS can be achieved in the proposed topology. Fig 5 shows that the secondary rectifier diodes can also achieve the soft switching.

When the current of auxiliary battery is positive, the battery transfers the power to the load and when it is negative, the auxiliary battery is charged. Fig. 6 and Fig. 7 show the current and voltage waveforms of the main battery during discharge and charge. Fig. 10 shows the estimated efficiency plot of the proposed three-port converter. As shown in Fig. 10 the maximum efficiency of the proposed converter is 96.4% at the medium load condition.

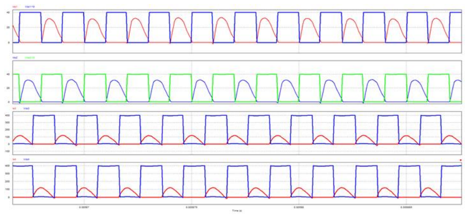
Fig. 4 Inverter switch current and voltage waveforms

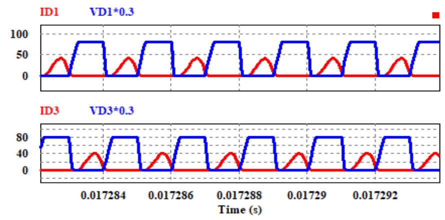

Fig. 5 Rectifier current and voltage waveforms

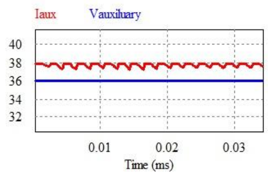

Fig. 6 Auxiliary battery as source

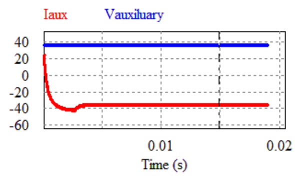

Fig. 7 Auxiliary battery as load

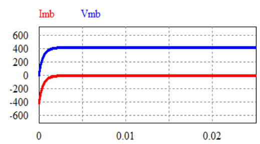

Fig. 8 CV mode for main battery

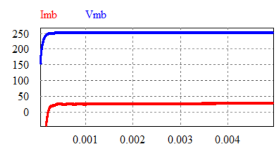

Fig. 9 CC mode for main battery

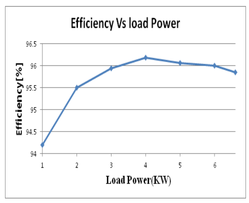

Fig. 10 Efficiency plot of the proposed 3-port converter

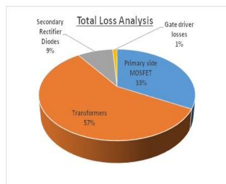

Fig. 11 Loss Analysis

4. Conclusion

In this paper a novel three-port converter for the On-Board Charger of Electric Vehicles is proposed Since the power flow is controlled by using an impedance control network, the proposed system does not require extra switches used to control the power flow between ports Therefore the cost and the size of the charger can be reduced Based on the equivalent circuit the circuit analysis was performed and the design equations for the proposed converter were presented Simulation results show that the proposed converter can achieve soft switching thereby exhibiting a high efficiency characteristics

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