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Three-phase high frequency transformer isolated AC to DC converter for EV battery quick charging

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***Abstract*— this paper proposed a three phase AC to DC converter, which is isolated by high frequency transformer, for EV battery quick charging. EV battery chargers normally need a transformer to isolate the power grid from battery system for safety. Different types of chargers exist. Some types that are isolated by commercial frequency transformer are of large volume and weight. By increasing frequency, the volume and weight of transformer can be greatly reduced. But the material that is proper for very high frequency can hardly be used for large power applications, by the reason of manufacturing and cost. The principle and design of this converter was studied. The fundamental operations were confirmed by 37 kW experimental results. Weight of transformer is reduced to about 1/7 and total efficiency is higher than 90%. 2-ARM-PWM method is studied for the purpose of loss reduction.**

Keywords-isolated; EV charger; CHAdeMO; high frequency;

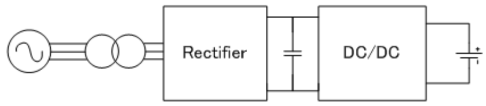
I. INTRODUCTION

The first electric vehicle was invented in the middle of 19th century. But the internal combustion engine (ICE) vehicle quickly dominated the market due to the much higher energy density of gasoline. While, as the problem of environment pollution and energy crisis getting worse and worse, electric vehicle (EV) is back to the game and attracting more and more focus in recent years [1].

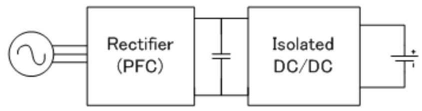
Battery charging is a very important issue for wide spreading of EV. Normally, the vehicle is imbedded with an inexpensive, light weight and compact charger with AC plug for slow night charging at home. Depending on the capacity and depth of discharge, the charging time takes about 6-8 hours. On the other hand, a quick charging station is also necessary for long distance travel and convenience. This off-board charger should provide over 100A DC current and make the battery to attain 80% state-of-charge in about 15 minutes.

A conductive EV quick charger standard *CHAdeMO* was proposed by multiple automobile and charger manufactures [3]. This standard requires a transformer to provide galvanic isolation between power grid and battery system for safety and the charging current must follow the instruction of battery management system on the car.

There are normally two kinds of topology for conventional EV quick charger that meets *CHAdeMO*. As shown in Fig.1a, the isolating transformer is located at the input side; a three-phase rectifier converts the AC voltage to DC voltage, then a DC/DC converter regulates the desired charging current for battery. Another kind of topology is shown in Fig.1b; electrical isolation is realized by the transformer in a DC/DC converter [4]. Matrix converter can also be employed to save the DC link capacitor [5]. For off-board charging, inductive modes also attract many researchers attention [2].



a) Commercial frequency 3-phase isolated type



b) High frequency isolated DC/DC type

Figure 1. Different types of EV charger

This paper studied the principle and design of a 37 kW three phase EV quick charger with 1 kHz isolating transformer. The topology was analyzed. Simulation and experiment results were presented, and improving method was studied.

II. ANALYSE OF PROPOSED SYSTEM

The main circuit of quick charger that is proposed in this paper is shown in Fig.2. The battery is electrically isolated by a transformer which is located between the output of inverter and the input of load rectifier.

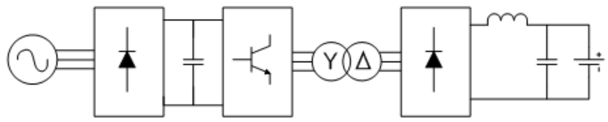


Figure 2. Main circuit of proposed system

A. Analyse of topology

The AC input voltage is converted to DC voltage by an uncontrolled rectifier. Then, the inverter transfers the DC voltage to high frequency alternative pulse. The high frequency transformer can isolate the input and output, and prevents 3× n order harmonics due to star-delta structure of transformer. The basic electromagnetic equation of transformer is

$$U = 4.44 \cdot N \cdot \Phi_{\max} \cdot f \tag{1}$$

Where U is primary voltage, N is primary turns, f is frequency, Φ_{max} is the largest magnetic flux.

If primary voltage is constant, N and Φ_{max} can be reduced by increasing the frequency.

And

$$\Phi_{\max} = B_{\max} \cdot S \quad (2)$$

Where, S is the cross-section of core leg.

The volume of core and length of coil will be smaller accompanied with the reduction of cross-section of core leg. Less turns lead to reduction of area of the core window. All above devote to a smaller volume and weight of the transformer, which also means less material consumption. In addition, the three-phase system is of higher power density than the single phase system.

According to *CHAdeMO* standard, the magnitude of the charging current is determined by instruction from the battery management system on EV. So the real time charging current is detected and compared with the instruction value. The error is used to change the modulation signal, which results in the corresponding variation of output voltage of the inverter and the DC charging voltage.

B. Design consideration

1) Operating frequency:

As discussed above, higher frequency can reduce the volume and weight of the transformer. The commercial frequency transformer that used in conventional EV quick charger is normally constructed by silicon steel. It is cheap but can hardly be used in frequency higher than 2 kHz because of loss. While ferrite core, which is widely used in high frequency switching converter application, is of higher price. In addition, higher frequency would result in more switching loss and magnetic loss.

Through comparison of massive design results of the transformer, the case of 1 kHz is of good performance on total consideration of volume, efficiency and cost.

2) Switching frequency:

As 1 kHz is selected as the operating frequency, 15 kHz is selected as the carrier frequency to get 15 pulses in every cycle. So, the harmonics can be under the acceptable level.

3) Hardware and software

Time to market is one of the most important issues for a new product. In the case of this paper, a commercialized high frequency output inverter is employed for the primary side of high frequency transformer. Universally imbedded software of variable voltage constant frequency (VVCF) control strategy can also be inhered for EV charging application.

Because of the high frequency output, the three-phase rectifier at the second side of the transformer should use high-switching-speed diodes.

C. Simulation result

To verify the design considerations, a simulating model is constructed. The output line-to-line voltage and line current of inverter are shown in Fig.3. By FFT calculation, the frequency distributions of them are shown Fig.4. The simulation results agree with the design.

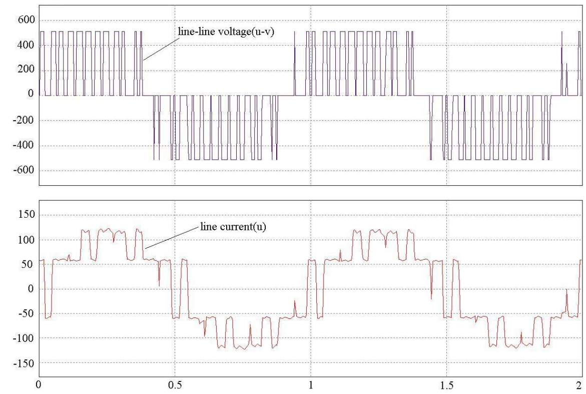


Figure 3. Output voltage and current wave of inverter

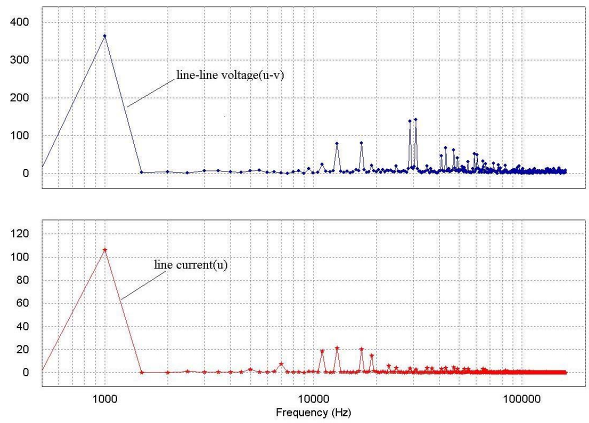


Figure 4. Frequency analysis of voltage and current

III. PROTOTYPE AND EXPERIMENT

Two 15kVA transformer prototypes, which are designed for 400Hz and 1 kHz respectively, were constructed. The comparison between them and the transformer of 50Hz is listed in Table I . The photo of 50Hz transformer is shown in Fig.5. The photo of 400Hz and 1 kHz transformers is shown in Fig.6.

TABLE I. COMPARISON OF TRANSFORMERS

Frequency/Hz	50	400	1,000
Weight/kg	170	32	23
Weight ratio	1	0.21	0.14
Size (W*D*H)/mm	400*300*470	470*150*300	350*163*272
Size ratio	1	0.38	0.28

The size of 1 kHz transformer is about 1/4 of 50Hz transformer, and the weight is reduced to about 1/7.

Figure 5. Photo of transformers for 50Hz

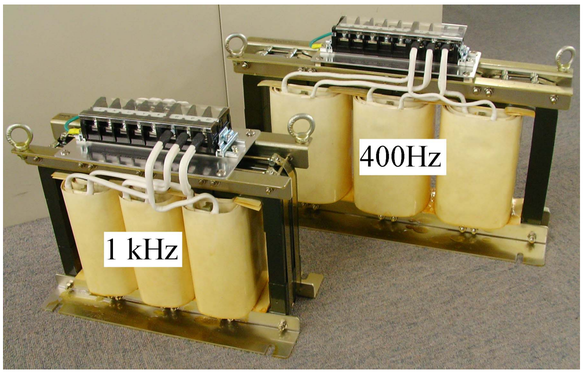


Figure 6. Photo of transformers for 400Hz and 1,000Hz

For the purpose of verification, a 37 kW experimental platform is built, and the circuit is shown in Fig.9. This platform is composed by a Fuji high frequency three phase inverter, a high frequency transformer and a three phase rectifier. As the main purpose of this experiment is to evaluate the operation and efficiency under different load conditions, a 37kW resistor is employed as a load to simulate the battery. The output line voltage and current of inverter is shown in Fig.7 and Fig.8, full load and half load respectively. These show good incidence with the simulation results.

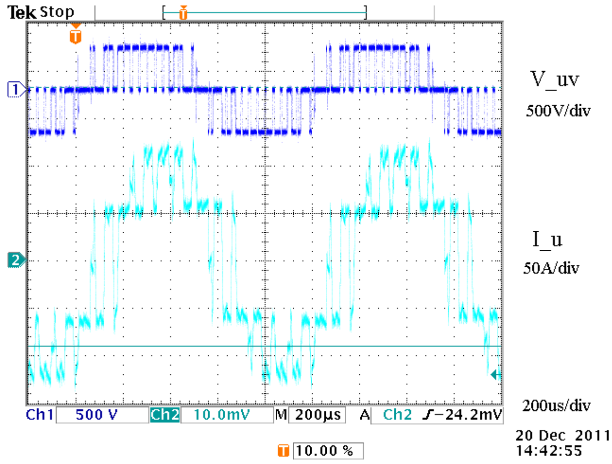


Figure 7. Output voltage and current wave form of inverter (full load)

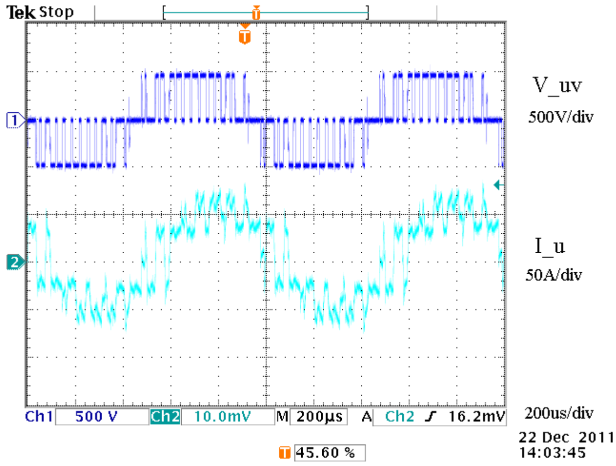


Figure 8. Output voltage and current wave form of inverter (half load)

TABLE II. EFFICIENCY AND TEMPERATURE RISING (3-ARM PWM):

Load	100%	75%	50%
Efficiency	90.73%	90.28%	89.86%
T_r (K)	96	71.3	47.7

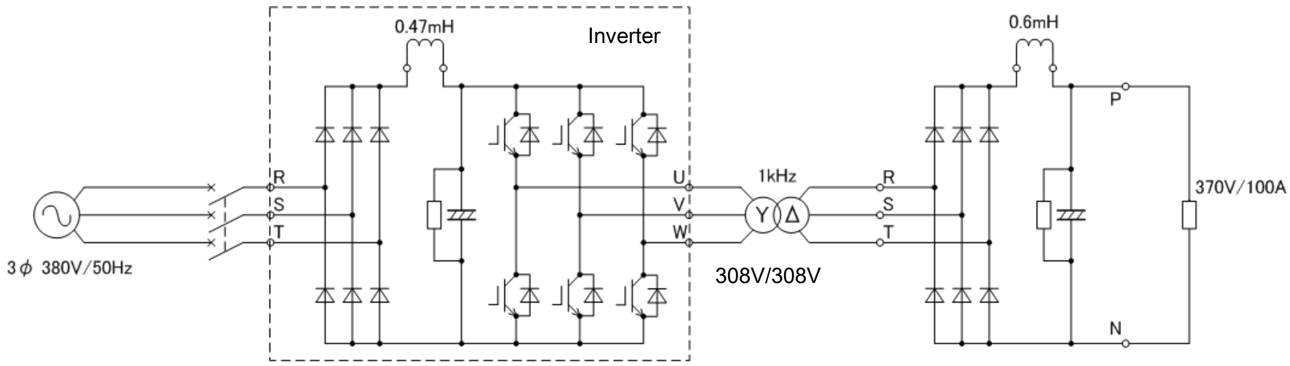


Figure 9. Experiment circuit of proposed EV quick charger

The total efficiency and temperature rising of IGBT case under different load conditions were shown in Table Ⅱ. As the safe limit is 70K, the result didn't satisfy the requirement, apparently. Loss analyzing and efficiency improving method were presented in the next chapter.

IV. IMPROVEMENT

The loss of inverter is composed of several parts: switching loss and conduction loss of IGBT modules and converter module, loss of DC reactor and driving loss, etc. IGBT module's type is 2MBI400U4H-120-54 of FUJI, and primary diode's type is PVC550A-16 of NIEC. The DC resistance of DCR is 0.05Ω. The loss breakdown of inverter is shown in Fig.10. IGBT modules devote 69% loss of inverter. The loss breakdown of IGBT module is shown in Table Ⅲ. Under a full load, the switching loss devotes 87.2% of IGBT total loss. At 75% and half load situation, the ratio is 83.7% and 85.1% respectively.

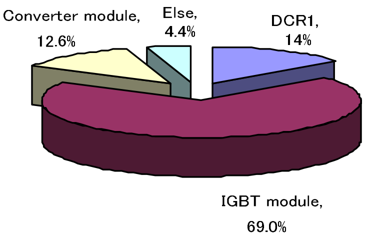


Figure 10. Loss breakdown of inverter

TABLE III. LOSS BREAKDOWN OF IGBT MODULE

Load	37kW*100%	37kW*75%	37kW*50%
SW loss/W	1425	1065.9	751.4
Cond. loss/W	298.5	207.6	132
Total loss/W	1723.5	1273.5	883.4

According to the analyses above, the main reason of high temperature rising on IGBT case lies in switching loss. This part of loss need to be reduced to satisfy the safety request.

A modulating method that is named as 2-ARM-PWM is employed [6]. In a 3-phase 3-line system, there are only two freedoms because of the restriction:

$$u_u + u_v + u_w = 0, \tag{3}$$

Where u_u ,u_v ,u_w are phase voltage.

As for standard sinusoidal pulse width modulation (SPWM), the modulating signal is given as

$$e_u = |V| \cdot \sin(\omega_1 t)$$
$$e_v = |V| \cdot \sin\left(\omega_1 t - \frac{2\pi}{3}\right)$$
$$e_v = |V| \cdot \sin\left(\omega_1 t - \frac{4\pi}{3}\right)$$

As a result, the line-line voltage will be

$$e_{uv} = \sqrt{3}|V| \cdot \sin\left(\omega_1 t + \frac{\pi}{6}\right) = e_u - e_v$$
$$e_{vw} = \sqrt{3}|V| \cdot \sin\left(\omega_1 t - \frac{\pi}{2}\right) = e_v - e_w$$
$$e_{wu} = \sqrt{3}|V| \cdot \sin\left(\omega_1 t - \frac{7\pi}{6}\right) = e_w - e_u$$

While the modulating signal is given as

$$e_u^* = e_u + f$$
$$e_v^* = e_v + f$$
$$e_w^* = e_w + f$$

It will result in the same three phase line-line voltages as 3-ARM-PWM. Different function f can be selected for different target.

Table Ⅳ presented modulating signals of the 2-ARM-PWM method. This name comes from the fact that there are always only two arms of the switches switching at any time in a period. So the total switching times reduced by 1/3.

TABLE IV. 2-ARM-PWM METHOD

	e_u^*	e_v^*	e_w^*
$0 \sim \frac{\pi}{3}$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t + \frac{\pi}{6}\right) - 1$	-1	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{\pi}{2}\right) - 1$
$\frac{\pi}{3} \sim \frac{2\pi}{3}$	1	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t + \frac{\pi}{6}\right) + 1$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{7\pi}{6}\right) + 1$
$\frac{2\pi}{3} \sim \pi$	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{7\pi}{6}\right) - 1$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{\pi}{2}\right) - 1$	-1
$\pi \sim \frac{4\pi}{3}$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t + \frac{\pi}{6}\right) + 1$	1	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{\pi}{2}\right) + 1$
$\frac{4\pi}{3} \sim \frac{5\pi}{3}$	-1	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t + \frac{\pi}{6}\right) - 1$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{7\pi}{6}\right) - 1$
$\frac{5\pi}{3} \sim 2\pi$	$-\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{7\pi}{6}\right) + 1$	$\sqrt{3} \cdot \lvert V \rvert \cdot \sin\left(\omega_1 t - \frac{\pi}{2}\right) + 1$	1

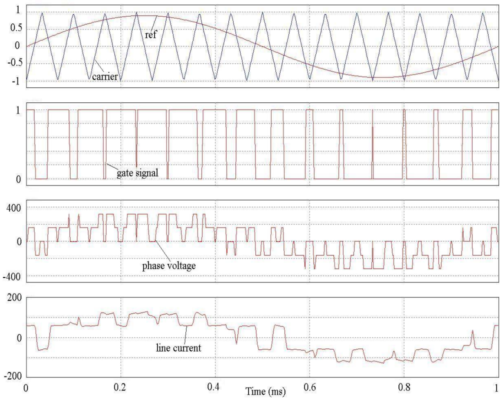
The wave forms of simulation results of 3-ARM-PWM method and 2-ARM-PWM method are shown in Fig.11. In the case of EV quick charger, power factor is always close to one. So, the phase angle of current is also close to that of voltage. Compare to the 3-ARM-PWM method, the switching actions at the peak of current did not occur in 2-ARM-PWM method. That means more than 1/3 of switching loss can be saved. On the other hand, the current waveforms remain almost the same, as shown in Fig.12. By FFT calculation, the frequency distribution of these two currents is shown in Fig.13. When the 3-ARM-PWM method is replaced by 2-ARM-PWM method, THD increased from 42.6% to 44.8%.

The temperature rising is determined by the loss and the thermal resistance, and the relationship is basically linear. From Table Ⅱ and Table Ⅲ, the relationship between temperature rising and loss can be deduced as

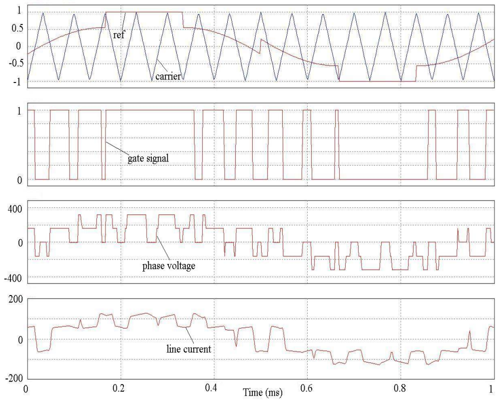
$$T = \left(\frac{71.3-47.7}{1273.5-883.4}\right)(P-883.4)+47.7 = 0.0605\mathrm{P}-5.746 \quad (4)$$

Where T_r is temperature rising and P is loss of IGBT.

By 2-ARM-PWM method, the expected efficiency of total circuit and temperature rising of IGBT module are shown in Table V. The temperature rising under full load can be expected to be 69.8K. It will meet the safety requirement.



a) 3-ARM PWM



b) 2-ARM PWM

Figure 11. Simulation result of 3ARM and 2ARM PWM

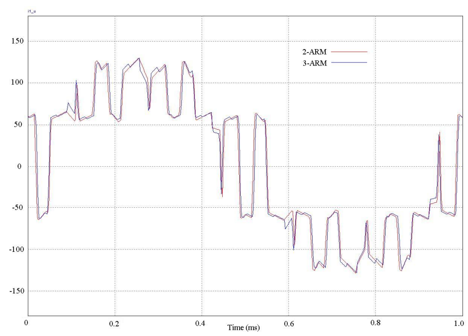


Figure 12. Comparison of current wave

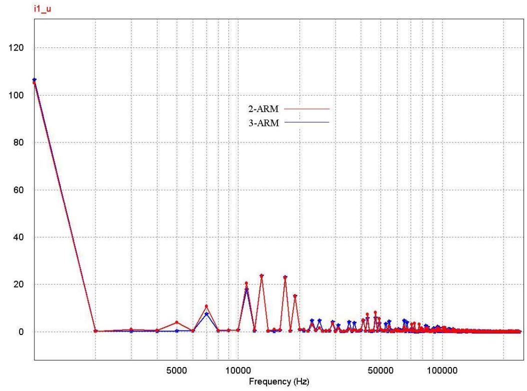


Figure 13. Frequency distribution of currents

TABLE V. EXPECTED EFFICIENCY AND TEMPERATURE RISING (2-ARM PWM):

Load	100%	75%	50%
Efficiency	91.8%	91.3%	90.94%
T_r (K)	69.8	49.8	32.5

V. CONCLUSION

In this paper, the principle and design of a three-phase high frequency transformer isolated AC to DC converter for EV battery quick charging is studied. The topology was analyzed. Simulation and experiment results were presented. Compared with the conventional EV charger with 50 Hz transformer, this high frequency isolated quick charger can reduce the weight of the transformer to about 1/7. The total efficiency is higher than 90%. To improve the efficiency of the inverter, 2-ARM-PWM method was analyzed. With a little increase on THD, the loss of IGBT modules can be reduced by about 1/3, and the temperature rising will satisfy the safety standard. The total efficiency of this 37kW converter for EV quick charging was improved by more than 1% at full, 75% and half load situation.

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