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HIGH POWER EFFICIENCY DESIGN APPROACH OF AN LLC RESONANT CONVERTER FOR UPS BATTERY CHARGER APPLICATION AND BATTERY CHARGE-DISCHARGE REGRESSION MODEL

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Abstract - *In this study, design procedure of inductor-inductor-capacitor (LLC) resonant DC-DC converter is developed for uninterruptible power supply battery charge applications based on high power efficiency. The LLC resonant converters have many advantages such as high-power efficiency and less switching losses when compared with other converters features. It is also capable of operating in narrow switching frequency where zero voltage switching can be provided. The DC-DC converter with 400V input and 48V/3.1A output has been selected as an experimental setup. In order to reach desired design of LLC resonant converter and required output values, switching frequency might be determined as above of resonance frequency via Power Electronics Simulation package program. The obtained maximum power efficiency was measured as 95.22%. Besides, charge-discharge models of the battery were obtained from the battery data obtained via deriving regression models with machine learning algorithms where battery electrical energy consumptions, battery status, and temperature data can be analyzed.* R^2 *and root mean square error scores are performed for different regression models. Random forest regression is determined as the best model among regression models for the obtained data set.*

Key words: *Energy, UPS battery charge, LLC resonant converter, machine learning, regression models*

1. INTRODUCTION

Uninterruptible power supplies (UPS) are devices that provide emergency electrical power to a connected device when the input power source fails [1]. Such devices are widely used in important sectors such as industry, healthcare, and military [2-4]. The batteries used in UPS must have satisfied the features such as smooth and quick charging, high power density, high efficiency. The charging of the batteries becomes very complicated due to the high voltages and currents involved in the system and the sophisticated charging algorithms [5]. The most commonly used battery charging architecture is shown in Fig.1. It consists of mainly two stages, namely power factor correction PFC stage and DC-DC converter stage. The power factor correction stage is a continuous conduction mode of boost topology [6]. DC-DC converter plays an important role in battery charger by regulating the output current and voltage.

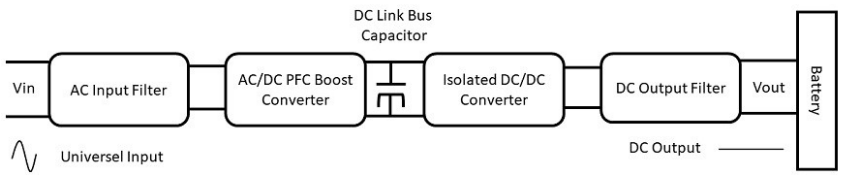

Fig. 1 Block diagram of a universal battery charger

It has been observed that LLC resonant converters are generally used in electrical vehicles battery charger applications because high power density and high efficiency battery chargers should be designed to have less volume and cost of electrical vehicles [7-9]. In this study, design procedure of LLC resonant converter for UPS battery charger applications based on high efficiency and battery charge-discharge regression model is aimed. In the design procedure, 4x12V UPS battery is taken into consideration. Thus, LLC resonant converter should be regulated the output voltage in a wide voltage range with different load conditions according to typical charging profile of battery. For the design procedure, basic operation characteristics of LLC resonant converter is defined, and operation regions are discussed in terms of high efficiency. To achieve high efficiency, all essential parasitic elements, including junction capacitances of all semiconductor devices and the leakage inductance and magnetizing inductance of the transformer should be utilized to achieve Zero Voltage Switching (ZVS). ZVS switching topology typically use resonance techniques to force the voltage or current in a semiconductor switch to zero, resulting to the elimination or reduction of the switching losses [10]. It is basically soft switching technique. The operation regions of LLC resonant converter are discussed to regulate wide output voltage range. Therefore, the purpose of the study is designing an LLC resonant converter that will have 48V/3.1A output values to charge 4 x 12V / 30Ah batteries. The circuit is simulated using Power Electronic Simulation Software (PSIM). In addition, it is presented as secondary output to find the charge-discharge models under varying conditions by deriving the regression models with machine learning algorithms where the battery electricity energy consumption, battery status and temperature data can be analyzed. Root mean square error (RMSE) and R^2 score tests were used to compare the obtained results.

The remaining sections are as follows; in the second section, circuit design procedure, simulation results and regression models are explained. In the third section, the results from the comparison of model performances with each other is done. In the last section, conclusions and recommendations of the study are presented.

2. MATERIALS AND METHOD

The half-bridge LLC resonant converter is given in Fig.2. The main parts of this converter are Square wave generator, Resonant network, and Rectifier network.

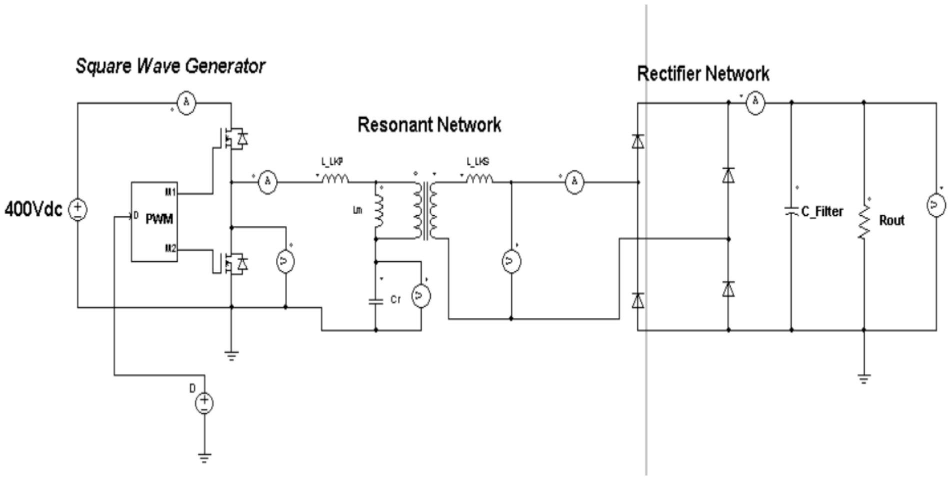

Fig. 2 The circuit schematic of LLC resonant DC-DC converter

The switching network produces a square wave voltage by alternating 50% duty cycle for each switch. The switching network can be full-bridge or half-bridge type. In this study, it is used as half-bridge type. The resonant network has a resonant capacitor, primary and secondary leakage inductances, and the magnetizing inductance of the transformer. The energy is transferred to the load with the help of transformers when the resonant converter allows the current to circulate. The resonant network filters the higher harmonic currents. Therefore, essentially only sinusoidal current is can flow from the resonance network, although square wave voltage is applied to the resonance network. The rectifier network consists of a filter capacitor and diodes. It produces DC voltage by rectifying the output of the transformer which is a sinusoidal voltage. This network can be full-wave bridge or center-tapped configuration [11].

2.1. Circuit Design Procedure

A dc/dc converter with 148.8W/48V output has been selected as a design for UPS battery charger. The design specifications are as follows; i) Input voltage: 400Vdc (output of PFC stage), ii) Output: 48V/3.1A (148.8W), iii) Holdup time requirement: 20ms (50Hz line freq.), and iv) DC link capacitor of PFC output: 220 μF. The design steps for the half-bridge LLC resonant converter are given below [12]. It is assumed that the efficiency is to be 0.88~0.92 for low voltage output and 0.92~0.96 for high voltage output, if its efficiency data are not provided, See Eq. (1).

$$P_{in} = \frac{P_o}{E_{ff}} \tag{1}$$

Mostly, LLC resonant converter operates around the resonant frequency (f_o) in normal operation to attenuate switching frequency variation. The gain at f_o is magnetizing inductance divided by primary side leakage inductance (k = L_m/L_{lkp}). Therefore, the value of k should be chosen to obtain the minimum gain. Mostly, k is chosen 5~10. See Eq. (2) and Eq. (3).

$$M^{min} = \frac{V_{RO}}{\frac{V_{in}^{max}}{2}} = \frac{L_m + L_{lkp}}{L_m} = \frac{k+1}{k} \tag{2}$$

$$M^{max} = \frac{V_{in}^{max}}{V_{in}^{min}}.M^{min} \tag{3}$$

The ratio (k) between L_m and L_{lkp} is chosen as 9.4. LLC resonant converter contains full-wave bridge rectifier for the rectifier network. The transformer turns ratio should be determined for full-wave bridge rectifier. See Eq. (4).

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{Max}}{2(V_o + 2V_f)} M^{min} \tag{4}$$

Where V_f = 0.7V. Transformer turns ratio obtained from Eq. (4), the equivalent load resistance is should be obtained. See Eq. (5).

$$R_{ac} = \frac{8n^2}{\pi^2} \frac{V_o^2}{P_o} E_{ff} \tag{5}$$

The resonant network parameters should be determined to achieve soft switching. See Eq. (6), Eq. (7), and Eq. (8).

$$L_p = L_m + L_{lkp} = \left(k+1\right) L_{lkp} = \frac{\left(k+1\right)^2}{\left(2k+1\right)} L_r \tag{6}$$

$$L_r = L_{lkp} + L_m // L_{lkp} = L_{lkp}\left(1 + \frac{k}{k+1}\right) = \frac{1}{\left(2\pi f_o\right)^2 C_r} \tag{7}$$

$$C_r = \frac{1}{2\pi Q \cdot f_o \cdot R_{ac}} \tag{8}$$

The calculated parameters and magnetic component values for simulation are summarized in Table 1.

Table 1. Values used for simulation

Parameters	**Values**
E_{ff}	%96
P_{in}	155 W
P_{out}	148.8 W
N	4.375
R_{ac}	251.9 ohm
L_r	110 uH
L_{lkp}	57.78 uH
L_{lks}	2.879 uH
L_m	542.2177 uH
C_r	19.03 nF
L_p	600 uH
M min	1.1066
M max	1.22
Np : Ns	36 : 8
Q	0.302
K	9.4

2.2. Simulation Results

LLC Resonant topology was built in PSIM software. The duty cycle is 0.5 and resonant frequency is 110 kHz. In order to reach desired design of LLC resonant converter and required output values, switching frequency was determined as above of resonance frequency, based on theoretical calculations and PSIM Simulation software. Therefore, the switching frequency is 115 kHz. Obtained efficiency is 95.22% and that zero voltage switching has been achieved as shown in Fig.3. The intersection area between voltage and current of MOSFET is very less.

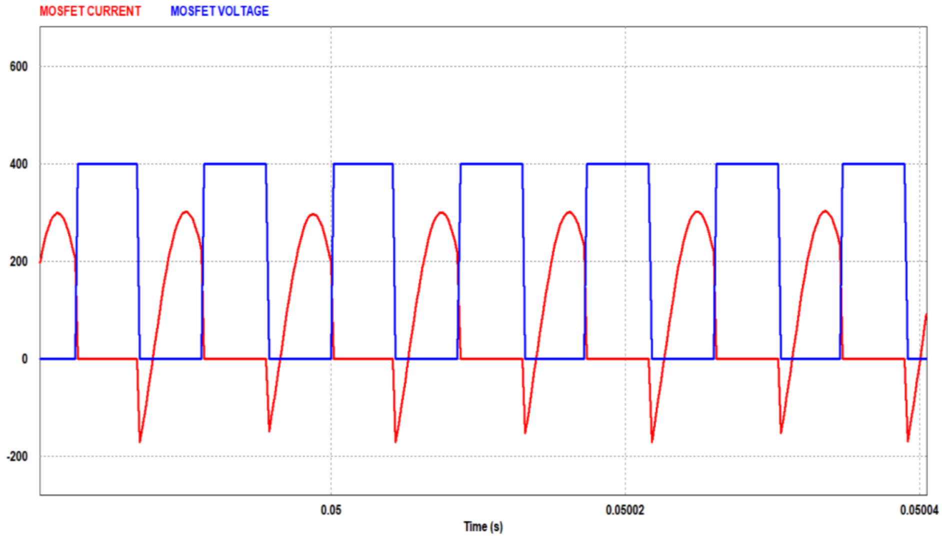

Fig. 3 MOSFET voltage (blue) and current (red) achieving soft switching

The output result of the PSIM Simulation were obtained as shown in Fig.4. The output voltage is 47.67 V and the output current is 3.07 A which are very close to required values.

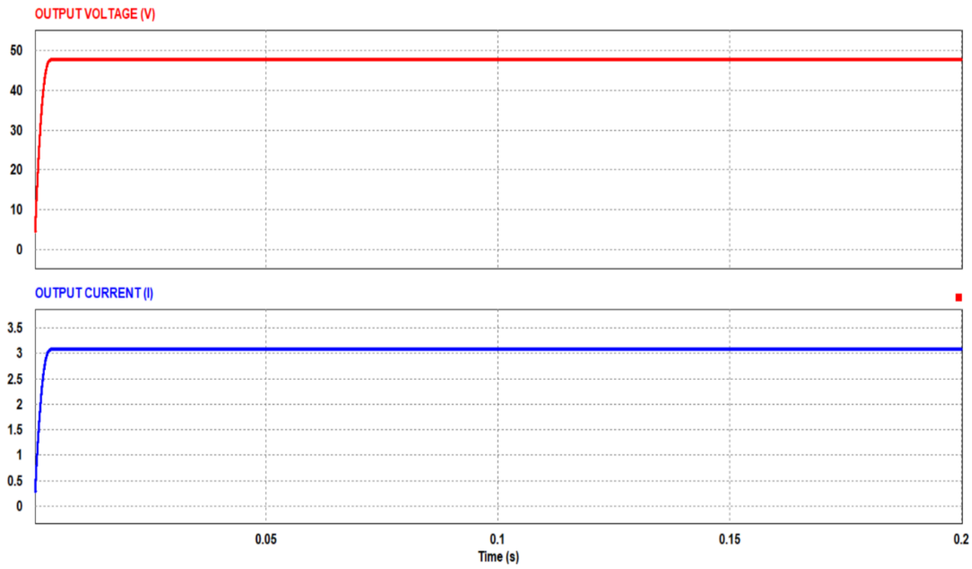

Fig. 4 Output Voltage (red) and output current (blue) of the LLC Resonant Converter

2.3. Regression Models

Regression analysis is a process of statistical methods which is used to estimate relationships between dependent and independent variables. The purpose of machine learning algorithms is learning to recognize the pattern with several different methods. For example, some of them are decision tree, linear regression, support vector machines, artificial neural networks, and k-nearest neighbor. Machine learning algorithms are divided into two groups: supervised learning and unsupervised learning. Regression models are in the group of supervised learning [13]. In this study, it is aimed to provide battery charge-discharge regression model to predict how long a battery with a known charge rate can be discharged according to the load and its medium temperature.by using machine learning algorithms.

3. Result and Discussion

Charge-discharge models of the battery is made by deriving regression models with machine learning algorithms. The data set is obtained from the 10kVA UPS produced by TESCOM A.Ş [14]. There are 4 different variables in the dataset which are discharge current, battery percentage, temperature, and battery usage time. The overall dataset was preprocessed and analyzed thoroughly. Different regression models were used to obtain battery charge-discharge regression models. These are linear, polynomial, light gradient boosting machine (LGBM), extreme gradient boosting (XGB), gradient boosting, random forest, decision tree, and K-neighbors regression. When applying these regression models, battery charge percentage and estimated time variables in the data set were used and to evaluate their performances RMSE and R^2 score are used. See Eq. (9) and See Eq. (10).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{m}(y_i - \grave{y}_i)^2}{m}} \tag{9}$$

where y_i is the time variable, $\grave{y}_i$ is the value of the predicted time of the regression model.

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{m}(y_i - \grave{y}_i)^2}{\sum_{i=1}^{m}(y_i - \tilde{y}_i)^2}\right] \tag{10}$$

where y_i is the time variable, $\grave{y}_i$ is the value of the predicted time of the regression model and $\tilde{y}_i$ is the is the average value of the time variable.

Finally, random forest regression model has been decided as best model among different regression models as shown in Table 2 where the lowest RMSE value and the R^2 score value is closest to 1. It is depicted in Fig.5.

Table 2. RMSE and R^2 score values of regression models

Regression Models	RMSE	R^2 Score
Linear Regression	77.2032	0.9946
Polynomial Regression	70.5056	0.9956
LGBM Regression	465.0893	0.8065
XGB Regression	93.0894	0.9922
Gradient Boosting Reg	70.8098	0.9955
Random Forest Regression	67.843	0.9959
Decision Tree Regression	128.161	0.9853
K-Neighbors Regression	104.8204	0.9901

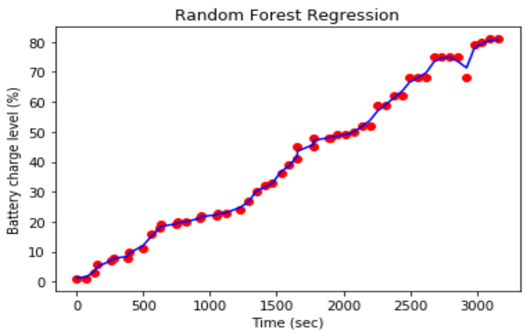

Fig. 5 Battery charge level versus time

4. Conclusion and Recommendations

LLC resonant DC-DC converter was designed to achieve high efficiency in UPS battery charging applications. LLC resonant DC-DC converter was chosen because the LLC resonant converters have many advantages such as high-power efficiency, less switching losses, and operating in narrow switching frequency where zero voltage switching can be provided when compared with other converters features. Battery charge-discharge regression model is made by using machine learning algorithms, where battery status, battery electrical energy consumption and temperature data were analyzed. Root mean square error and R^2 score tests were performed for different regression models. The tests are generated in Python and the results of them are compared to each other. Random forest regression has been decided as the best regression among regression models for the obtained data set. Finally, it can be predicted how long a battery with a known charge rate can be discharged according to the load and its medium temperature. As a future work of this study could be the hardware implementation for the system and the data can be obtained from the real time application. In addition, more research can be done to make the system perform better.

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