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Dear Dr Bhat

Please accept the accompanied 399 report entitled “Design of an Inductive charger for use on Electric Vehicles”

This report is the result of work completed throughout the course of the summer 2012 University Of Victoria term for the course Elec 399. During this course our group was tasked with selecting and researching a design project of our choice. We decided on this project based on the relevant interests of the team and the potential to carry on research into a 499 project.

While working on this report we were afforded the opportunity to learn about the intricacies of inductive charging and the process of team management and task designation.

We would like to thank you for your time helping and the project proposal which has served as the basis of our project.

Allen, Brayden, Jason, Neil, Nathan

ELEC 399: Design Project I

Final Report

Design and Build a DC-DC Convertor for Charging Electric Vehicle Batteries

Group: 14

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Chapter 1: Goals

The project selected was to design a charging system for electric vehicle battery packs. The project was selected with the intent of furthering “green” energy technologies and accommodate for the increasing demand for economic and efficient electric vehicles. This increasing demand for electric vehicles presents a wide market for electric vehicle battery chargers, which provides a very large commercial potential for such designs.

The goal of the project was to design DC-DC converter to help charge an electric vehicle battery faster, more efficiently, and most importantly safely. The main concept of the design was to use an LCL type resonant converter configuration with a clamping type high-frequency transformer that would be magnetically coupled to the vehicle for added safety.

Additionally, it was aimed to design an intuitive and easy to use charging process using a microcontroller in order to control the power output based on the charging state of the battery. The state feedback from the battery to the microcontroller was planned to be as non-intrusive as possible in order for the system to be easily implemented on all electric vehicles.

The project was mainly focusing on the design phase with the potential to continue on with prototyping, testing and optimizing phases in the future. The planned deliverables of the project were detailed schematics and a parts list for the design of the DC-DC converter.

Chapter 2: Overview

This report will detail the criteria used in the selection of individual charger components and analyze the different options available. By looking into future growth markets and current government policies on electric vehicles a more complete plan can be assembled to ensure that the charger meets not only technical requirements but fulfils the societal need. Patent infringement issues will also be addressed to ensure no legal threats arise.

Concluding this report will be a detailed description of sample values calculated which can be used should the project move ahead into the prototype stage.

Chapter 3: Detailed Project Description

Supply

Rectifying the standard 220V AC household supply will result in a DC input voltage of approximately 250 VDC.

Designing a full scale car charger would result in a prototype with few practical applications. By scaling down the design to a 30VDC input 15VDC output the prototype could be used with many standard RC cars. This smaller scale would demo much better and be easier to test for usability.

Converter Selection

The two most popular converter configurations are the series resonant and parallel resonant converters. Historically the series resonant converter encounters voltage regulation problems under light loads while circulating currents in parallel resonant converters lead to lower efficiencies at light loads.
By adding a parallel inductance to the primary or secondary side of the transformer winding in a series resonant converter the light load voltage regulation issues can be overcome, while still maintaining the favourable series resonant traits provided it is operated above resonance.

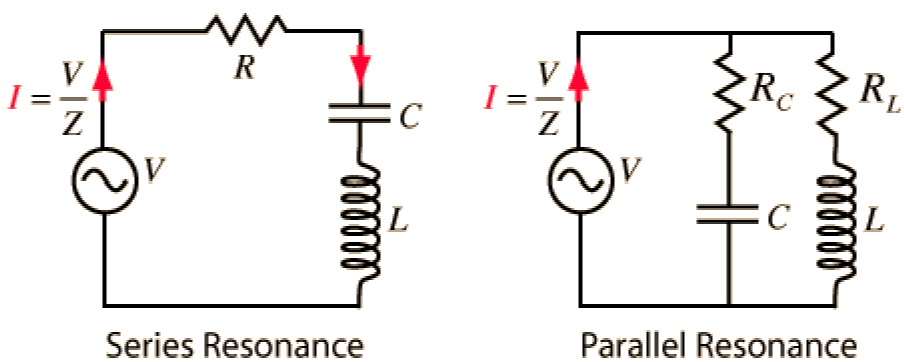

Figure 1-Series and Resonant Circuits

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/serres.html

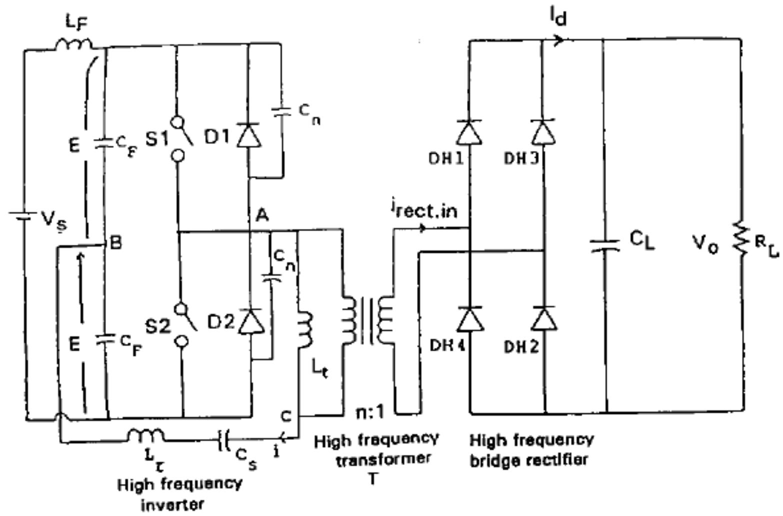

Figure 2-Half Wave LCL Series Resonant Circuit

The LCL converter configuration has a number of advantages such as the ability to accommodate a wide range of input and output voltages, can operate both in step up and step down modes, soft switching and can be accomplished over an entire operating range.

An LCL circuit is used to minimize the output current ripples present in DC-to-DC converters and strives to provide a clean sinusoidal wave output. Another advantage to this converter is the reduced Electromagnetic Interference (EMI) and stresses while also having a high power density. An example of a series resonant converter in action is depicted below.

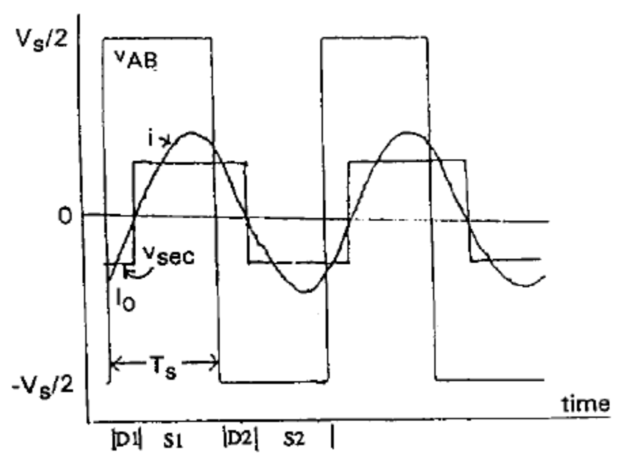

Figure 3-Waveforms for different points in the LCL-type series resonant converter of Fig.2

The circuit will be designed to operate in Continuous Conduction Mode (CCM) as it allows for the lowest peak to average current ratio for the converter throughput power. This provides a much more effective charging current for higher power applications like our Electric Vehicle charger.

Switching Circuit

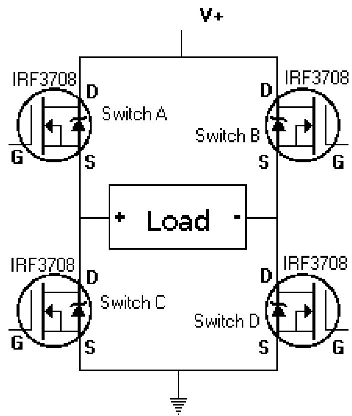

Figure 4-H-Bridge MOSFET Inverter

http://www.learn-c.com/experiment7.htm

Conversion of the DC input to square-wave AC for the LCL circuit will be accomplished using an H-Bridge MOSFET Inverter. It accepts a DC input voltage then using a gating signal which will be produced by our Arduino micro-controller switches the MOSFETs on and off to create the desired square wave signal. Turn off losses associated with this operation in our LCL design dictate that switches with fast turn-off times must be used. When calculating out values for your inductances and capacitances, ideal switches will be assumed to expedite calculations.

Bridge Rectifier

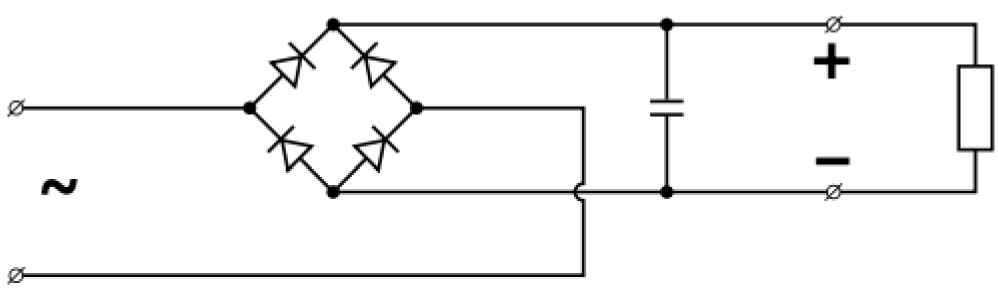

Figure 5-Diode Bridge with Smoothing Capacitor

http://en.wikipedia.org/wiki/File:Diode_bridge_smoothing.svg

At the output of the transformer secondary a Diode bridge with a smoothing capacitor will be used to convert the AC back into DC to charge the battery pack. It functions by inverting the negative portion of the AC waveform and the smoothing capacitor reduces the ripples between peaks of the inverted waveform, producing a reasonably constant DC current. Advantages of the full bridge system include:

- No requirements of center-tap transformer.
- For the same secondary winding voltage output this circuit will produce twice that of center-tap full wave rectifier circuit.
- For the same DC output the PIV is one-half of that of center tap full wave rectifier.

Calculation of Inductances and Capacitances

Design parameters:

V_{smin} = 30v
V_o = 15v
f_t = 100kHz

$$R_L = {}^{V_o}/_{P_o} = {}^{15^2}/_{20} = 11.25$$

$$R_L' = n^2 R_L = 2^2 * 11.25 = 45$$

$$\sqrt{{}^{L_s}/_{C_s}} = Q * R_L'$$
$${}^{L_s}/_{C_s} = (R_L')^2$$
$$C_s = {}^{L_s}/_{(R_L')^2}$$

$$\sqrt{{}^{L_s}/_{C_s}} = Q * R_L'$$
$${}^{L_s}/_{C_s} = (R_L')^2$$
$$L_s = C_s * (R_L')^2$$

$$\omega_s = {}^{1}/_{\sqrt{L_s C_s}}$$

$$C_s = {}^{1}/_{\omega_s R_L'}$$
$$C_s = 35.4_{nF}$$

$$L_s = {}^{R_L'}/_{\omega_s}$$
$$L_s = 71.6_{\mu H}$$

Effective parallel inductance calculation using the inductor ratio extracted from design curves.

$${}^{L_s}/_{L_p} = 0.2$$

$$L_p = 358_{\mu H}$$

For a practical 100kHz transformer with a ~2:1 turns ratio:

$$L_{1p} = L_{1s}' \approx 2.6_{\mu H} \qquad L_m \approx 1600_{\mu H}$$

Calculation of parallel inductance placed on the secondary side:

$$L_p = {}^{L_m L_t}/_{L_m + L_{1p} + L_t}$$ Given $L_{1t} << L_t << L_m$

$$L_t \approx {}^{L_m L_p}/_{L_m + L_p}$$

$$L_t = 292.5_{\mu H}$$

Calculation of series inductance on primary side:

$$L_r = L_s - L_{1p} = 71.6 - 2.6 = 69_{\mu H}$$

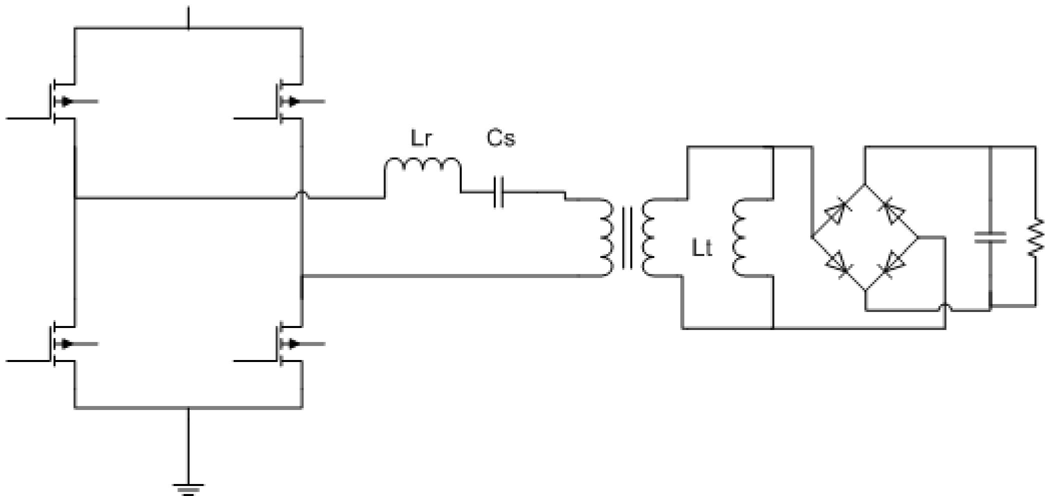

Figure 6-LCL-type Series Resonant Converter with Parallel Inductance on Secondary

Safety

An important aspect of the LCL converter design is the ability to magnetically couple to the vehicle using a clamping type-high frequency transformer. Although there will be no exposed metal connections on the interface between the car and charging station by magnetically coupling the two will prevent damage to anything or exposing conductors in the event the car is driven away without properly disconnecting the charging device. An issue may be encountered due to the United States Patent 7,311,526 held by Apple Inc., which covers techniques for coupling interfaces parts using moveable magnetic elements. This patent states that when the plug and receptacle are brought into proximity the magnetic attraction between the magnet and its complement, whether another magnet or a ferromagnetic material, maintains the contacts in an electrically conductive relationship. Similar patents are also held for deep fryer power cables and Microsoft, who designed a magnetically coupled connector for data transfer to phones. To navigate these held patents for similar devices a patent lawyer may be consulted to avoid future issues for patent infringement.

Charging Control Unit

It was decided that an Arduino microcontroller would be used for the main component of the overall charging control unit. Arduino is an open-source electronics prototyping platform designed with the purpose of connecting multidisciplinary electronics with ease. The board can be connected to a variety of sensors and controls that are capable of controlling lights, motors, and other actuators making the input/output capabilities of the microcontroller very versatile. The Arduino programming language used for the microcontroller is very similar to C++ and Arduino has its own development environment.

For the purpose of this project it would be most efficient to order a pre-assembled board and wire it to a separate prototyping board that will accept any other parts required for the design. By analysing the voltage characteristics of the secondary side of the clamping transformer the Arduino can use programmed logic to attenuate the charging current. This will be accomplished by modulating the gating signal frequency as the batteries charge. The design needs to be non-intrusive and easy to use on any electric vehicle without requiring any major changes in the vehicle design itself.

Although the original design requirements made eliminating exposed conductors a high priority; signal leads with exposed leads will likely be used to communicate battery charge capacity from the car to the charging station. These leads will be small signal leads transmitting signals to the controller and will pose no safety risk, therefore it has been decided that they do not counter our original design intent. Another potential option is including an instrument transformer in the design in order to measure the real time voltages which would allow software to calculate when the battery is fully charged.
Other options will be explored in the future with the intent of finding the most feasible option.

Testing and Debugging

A very important step of the design and implementation of this project is the testing stage. To ensure the proper operation of the circuit and protection of the components and operators, a test procedure will be developed to run simultaneously with the development and assembly of our charging circuit. The first step is confirming that all the components (inductors, capacitors, transformers, resistors, diodes, PCB) have arrived free from shipping damage or manufacturing defects. As the components are soldered to the PCB, it is imperative to observe the solder joints through a microscope to ensure the board is free from cold solder joints, cracked solder, solder splashes, and shorts. This visual inspection needs to be followed up with impedance testing, confirming continuity in the copper and at the joints. Once the circuit is operational, the operation of the Arduino needs to be confirmed. The Arduino will be outputting waveforms from four of its output pins to control the 4 H-bridge MOSFETs at our 100kHz frequency, therefore by connecting these outputs to an oscilloscope we will be able to verify the correct signals and frequency from the Arduino. Debugging will then be conducted within the Arduino's programming environment.

Finally, if there are still issues in the operation of the circuit, the outputs of the inverter can be hooked up to a multi-channel digital oscilloscope to observe the gating pulses and current waveform.

Chapter 4: Team Organization

Workload Distributions

The design team dynamic utilized each member's skills by allocating each person specific tasks suiting such strengths. The team was broken up into three different sectors: Research & Design, Conceptual and Theoretical Study, and Management. The research and design division was in charge of handling everything related to the designing and building the DC-DC converter for charging electric vehicle batteries.

The research and development team consisted of Allen Houle, Brayden McDonald, and Nathan Bellmore. The reason for having set people to handle the research and design was due to their specializations in power electronics and power systems and having their backgrounds in the field of the project allowed for easier conceptual understanding and also will lead to a better designed project. This division allocated tasks pertaining to the main project between the three team members such as researching charging circuitry, magnetic coupling device and patent searching to prevent legal issues.
The conceptual and theoretical study team was comprised of Jason Small, this involved reading, understanding and reciting the course readings. Using the information and techniques learnt from the chapters Jason was able to pass on critical information and beneficial techniques to further the design project. The management division was done by Neil Hindle, this consisted of understanding the goals and objectives needed for each deadline and delegating appropriate tasks. Accompanied with this position was formatting, referencing and revising reports as well as creating the team website.
The divisions of the group would combine to a single group when ones allocated task was complete, thus the workload was evenly distributed across the team. The benefit of designing the team architecture like this was the ability to divide the tasks equally over available resources. To have a single manager role in a team also provides stability as team mates know who to talk to for information about their specific task as well as what can be done next to advance the team.

Chapter 5: Project Discussion

A simulation was done using the values calculated for our series and parallel inductances can be seen below. Some issues and uncertainties were involved in this as the primary and secondary inductances of the simulated transformer had to be estimated and may not represent our actual transformer configuration.

The most difficult parameter to accurately simulate is the air gap present in our clamping type transformer; because we will not know how well we will be able to clamp the charger side to the vehicle side until a prototype is built, the estimations will have to suffice.

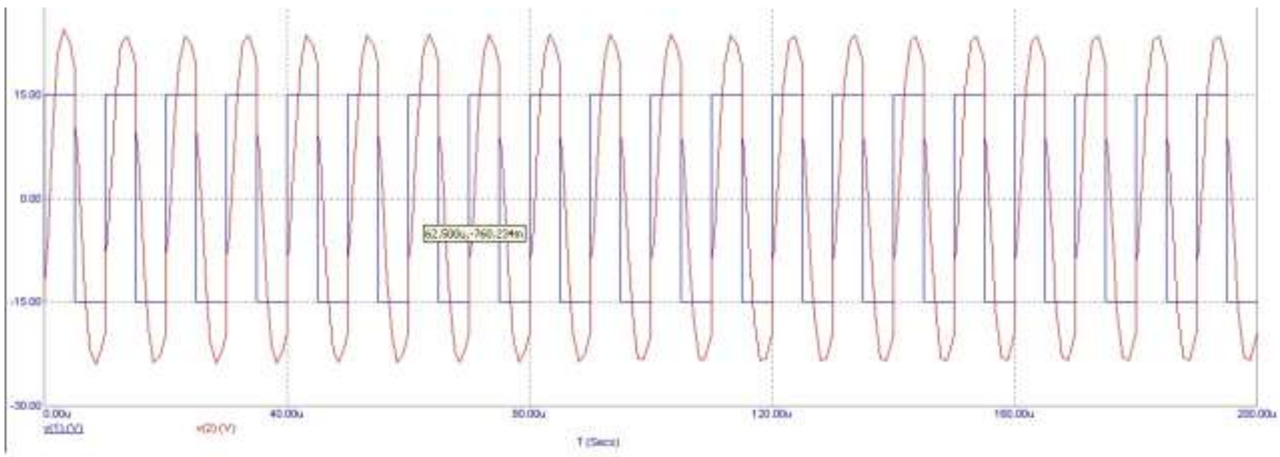

Figure 7-Simulation of LCL Input vs Transformer Output

This simulation is a fairly clean sinusoidal waveform coming off of the transformer secondary. It has few voltage spikes and indicates that our decision to use the LCL-type series resonant converter was the correct one.

Chapter 6: Summary and Future Works

Through the course of this project our team has learned a great deal about DC-DC converters and their intricacies. Inductive charging is the future of EV charging; the unparalled safety and ease offered by magnetically coupling the charger to the vehicle are vastly superior to competing methods.

Looking ahead, a prototype based on the sample values calculated should be constructed. This will allow real word testing which can both be used to charge smaller RC batteries and provide a base for which to design a larger charging system to be used in conjunction with actual EV technologies.

Appendix A: Textbook Review

Chapter 12: Moving into Implementation

This section focuses on what happens as the design phase finishes, and the systems analyst begins to work on the tasks associated with building the system, making sure it performs as designed and as per the customer's specifications. Different documents will also be written during this part of the systems development life cycle.

Managing Programming

Since programmers are only involved with the programming of the project, other responsibilities are left for the systems analyst during the implementation phase. This is also the project manager's busiest phase in the systems development life cycle. His first task is to efficiently assign projects and tasks to the programmers by being efficient in doing so, by assigning the minimum amount of programmers while still making deadlines and the projects requirements feasible. This minimization of programmers is due to the coordination and communication difficulties arising from an increased size in the programming team. However this coordination can be improved by having a structure management plan including regular meetings, ensuring standards are followed implementing change control, and using computer aided software engineering tools successfully.

The other main key function of a project manager is to manage the schedule and adjust according to delays. The ways of combating delays is to be aware of scope creep, where the scope of the project goes beyond the definition of requirements, and minor slippages that could go unnoticed.

Testing

Testing is one of the most important parts of moving to implementation of a system. After a project is completed fixing a large bug could demand time and resources that could far exceed the annual salary of a single programmer. A thorough testing plan should contain several individual tests that examine all aspects of the system. An effective test will have several test cases that can be examined by the testers.

Test planning has four general stages;

- Unit tests

  Focuses on one unit, just a program or program module. Ensures program or module works as specified.

- Integration tests

  Assesses whether a set of modules will work together as specified

- System tests

Run by the systems analyst to make sure modules and programs work together without error

- Acceptance tests

Performed by the user with support from the project team to confirm the system is complete and meets the business needs that prompted the system to be developed

Developing Documentation

There is a shift developing away from hard copy paper documentation to electronic copies. There are three types of user documentation;

- Reference Documents

Designed to be used when the user needs to know how to perform a specific function

- Procedure manuals

How to perform business tasks and tutorials teach people how to use the system

- Navigation controls

Search function hot linked indexes on online electronic documentation.

Chapter 13: Transition to the New System

An examination of processes needed to install an information system and teach an organization to successfully use it.

Making the Transition

A transition to a new system utilizes Lewin's three step model of organizational change

1. Unfreeze
2. Freeze
3. Refreeze

The activities during system analysis and design will help remove attachment and unfreeze the existing system. The migration plan guides the movement from the as is system to the new (to be) system. The sup[port and maintenance provided for the new system allows it to be set in the organization, refreezing the new system

Migration Plan

This plan encompasses a variety of elements that will guide the transition to the new system. It is a measurement of the organizations readiness to migrate to a new system. Understanding the sources of resistance to change and the costs and benefits that the users perceive will help the analysts develop a successful migration plan.

Post-implementation activities

System support from the operations group will provide online and help-desk support by the users. It has 2 levels of support staff; level one answers phones and handles questions, level two follows up on challenging problems and can generate change requests or bug fixes. Project team review focuses on the way which the team carries out its required activities, and documents key lessons.

Chapter 14: The Movement to Objects

This chapter explains the basic concept of object approach and UML, being able to create use case, class, sequence, and behavioural state diagrams. It describes the basic characteristics of Object oriented systems; the analysis and design of object oriented systems, and explaining the four fundamental UML diagrams.

1. Use case Diagram
    a. Illustrates main functions of a system and different kinds of users that interact with it. They can extend or include other use cases.
2. Class Diagram
    . Shows classes and relationships among classes that remain constant in the system, over time. Classes are related to each other through associations of behaviours.
3. Behavioural state machine diagram
    . The behavioural state machine diagram shows the different states that a single instance of a class passes through during its life in response to events, along with responses and actions

Appendix B: References

[1] A. K. Bhat, "Analysis and Design of LCL-Type Series Resonant Converter," IEEE Trans. Ind. Electron, Vol. 41, No. 1, pp. 118-124, 1994.

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