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WIRELESS CHARGING SYSTEM USING HIGH POWER, HIGH FREQUENCY MAGNETIC INTERFACE FOR UNDERWATER ELECTRIC VEHICLES

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ABSTRACT

This paper proposes to use a magnetic interface to convert the electric charging energy into a magnetic circuit that can couple the energy to the receiving equipment and get re-converted into electric charging current. The Charging head becomes one part of the charger where a high frequency ferrite core is used for creating a high frequency magnetic field in the frequency range 10-30 Khz and power levels of about 500Watts as proof of concept. A power inverter of 500W peak power rating is used to build this high frequency magnetic field creation. The inverter would be built with Power MOSFETs. The charging head, which is in the underwater vehicle, will have to be brought in close proximity to the charging head face without having to establish any electrical links. The charging head and receiving head faces are hermitically sealed for underwater operation. The control system proposed will be able to auto-detect the presence of the charge receiving head and ramp up the charging process to the energy amount needed for a full charge of battery in the underwater vehicle.

Keywords: wireless underwater vehicle, power MOSFET, magnetic field, charging, PWM modulation, transformer, magnetic interface.

INTRODUCTION

The power supplied to various devices in the underwater vehicles is provided from the rechargeable batteries. Whenever the charge [2] drains it has to be recharged using a plug-in system. The main disadvantage of relying on underwater cables to produce a plug-in system in the high salt water condition prevailing under sea is a difficult proposition. Salt water causes corrosion and such corrosion of electrical power coupling sockets can cause leakage currents that drain out the efficiency of such systems. Therefore to avoid corrosion and protect the marine ecosystem a suitable standard prototype wireless underwater charger is designed and built. The standard prototype system which can produce a modified sine wave is built to form the basis of converting electrical energy into a magnetic field and onward recovery of the energy by a pick-up head. The prototype system relies on a suitably designed inverter to form a sinusoidal magnetic energy generator of a suitable frequency to be used for the intermediate power transfer function and onward recovery of the energy in the pick-up head. A precise method in the process of generation of AC/DC/AC conversion-inversion is the modified sine wave. The modified sine-wave is a suitable method to generate higher frequency AC sinusoidal generators for this prototype since generating a pure sine wave at these frequencies presents difficult switching conditions for the MOSFET switches used in inverters.

SQUARE WAVE

This is one of the simplest waveforms an inverter design can produce and is best suited to low-sensitivity applications such as lighting and heating. Square wave output can produce large harmonics that is detrimental in any electrical system at power levels in excess of a few 100 watts.

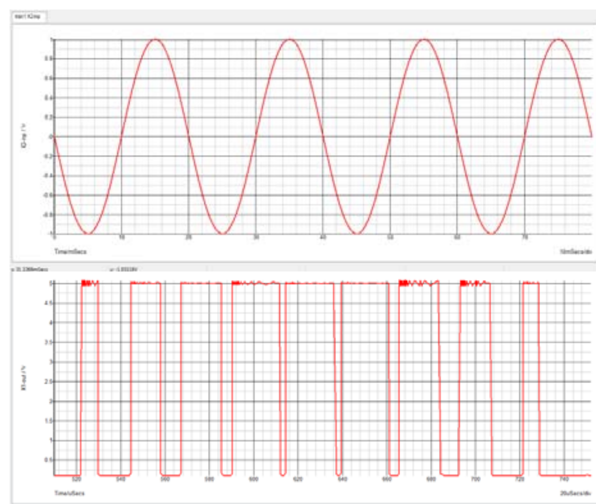

Figure-1. Models of sine wave and PWM wave.

SINE WAVE

A power inverter device which produces a multiple step sinusoidal AC waveform is referred to as a step sine wave inverter. These step switching designs are more economical when compared pure sine wave inverters. The switched design helps reduce harmonics when used with a suitable L-C filter network.

MODIFIED SINE WAVE

A "modified sine wave" inverter has a non-square waveform [3] that is a useful rough approximation of a sine wave for power translation purposes. In the modified sine wave inverter, there are three voltage levels in the output waveform, high, low, and zero with a dead zone between the high and low pulses. Most consumer power inverters produce a modified sine wave rather than a pure sine wave to trade cost with harmonic distortion. The waveform in modified-sine-wave inverters is in general produced using the method of Pulse Width Modulation (PWM).In a PWM based power transfer the ratio of ON to (ON+OFF) time can be adjusted to vary the effective average voltage while maintaining a constant switching frequency which is decided by the sum (ON+OFF) time, with the sum held a constant. The term duty cycle describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on. The MOSFET switches used for PWM based power transfer are realized by a suitably generated gate pulses are given to each switch in accordance with the developed pattern to obtain the desired output. Harmonic spectrum in the output depends on the width of the pulses and the modulation frequency. The generated gate pulses are given to the rapidly switching on and off power MOSFETs at high frequency (~50 kHz) can directly pulled from the Embedded controller which is operated at low voltage DC source and isolated and sent to the gate of the MOSFET switches through suitable isolating interface.

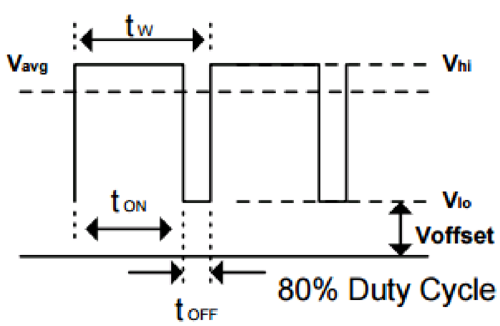

Figure-2. Timing diagram of duty cycle representation of square wave (Ton and Toff).

This PWM modulation technique used in a complementary manner with both positive and negative polarities using either a half-bridge[4] (using 2 MOSFET switches) or a full H-Bridge using 4 MOSFET switches enables realization of a PWM bases switched inverter of the desired frequency. The alternating power signal thus generated goes through step-up transformers to produce a higher voltage signal. The output of the step-up transformers then gets rectified and filtered by capacitors to produce a high voltage DC supply. In a proposed magnetic power transfer the primary part of the transformer core so used is in the charging head of the charger source and the secondary part is in the underwater vehicle and the magnetic coupling is realized when the secondary part or the pick-up head is brought to the vicinity of the charging head that has the primary part of the transformer.

BLOCK DIAGRAM

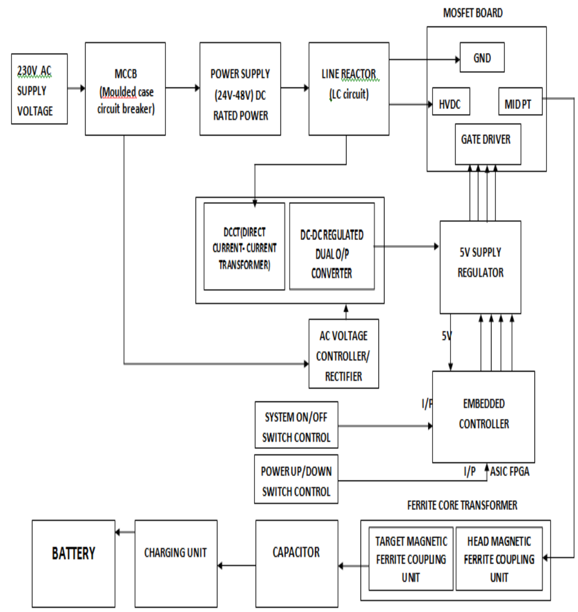

Figure-3. Block diagram of wireless charging.

POWER SUPPLY AND PARTS USED

A power supply is the hardware component that supplies power to the electrical device in this design. The main electricity is the general-purpose single phased 230v and 50Hz alternating-current (AC) line electric power supply is used as the input to the system through a suitable socket to power the charging head.

MCCB (MOLDED CASE CIRCUIT BREAKER)

Molded Case Circuit Breakers are designed to provide circuit protection for low voltage distribution systems. They will protect connected devices against both overloads and short circuits. Such a device is used to protect the power supply feed to the charging head.

POWER SUPPLY (24-48) DC RATED VOLTAGE:

The 230v AC voltage is reduced and used at ± 48V level through short-circuit protected Switched mode power supplies that are standard products available to be used in the prototype design. This ±48 V DC supply and given as input to the main inverter MOSFET switch board. The use of the standard switched mode regulators simplify the design as well as provide the most important feature of galvanic isolation of the inverter from the lines. These switched mode power supplies can be connected either in parallel or in series to either build larger current supplies or larger voltage supplies.

LINE REACTOR

Since the power transfer from the switched mode regulators is to an inverter line reactor which is also called as an inductor wired between a power source and the DC bus from which the MOSFET bridge would generate the switched inverter power signals. In current limiting function, the reactor serves to filter out spikes of current

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and may also reduce injection of harmonic currents into the power supply.

DCCT (DC–CURRENT TRANSFORMER)

DC current transformer is used to measure the current that is switched by the MOSFET bridge. Since the inverter operates at frequency ranges from 10 - 35 Khz, standard CT (Current transformer) is not feasible. It works on the hall effect principle and so preserve the current waveform for monitoring and control of the inverter and the MOSFET bridge. DCCTs are bipolar and so both the negating and positive half cycles of the current through them can be monitored.

DUAL MOS HALF BRIDGE

The dual MOS half bridge board consists of two MOSFET switch, Bridge gate drivers built with dc-dc converter and opto-coupler to connect the gate signal to the power MOSFETs. The inverter MOSFET bridge can operate in a wide range of voltages with this isolated gate firing arrangement and this range can be from 24 VDC to about 600 V DC with the MOSFET themselves rated for a max DC voltage operation of 1200 V DC.

GATE DRIVERS

Gate driver is a power amplifier that accepts a low-power input from a controller IC and produces the appropriate high-current gate drive for a power MOSFET. MOSFET gates are highly capacitive and so a large charging current has to be sourced when the device is to be turned on. The gate drive is between the GATE and the SOURCE of a MOSFET, each MOSFET in the bridge has to have a GATE power supply that is galvanic isolated from the other MOSFET gates. So the gate of each MOSFET in a bridge needs its own gate power supply and a opto-coupler to provide a signal from a control element from a suitable electronic circuit like a microcontroller or other suitable hardware that generates the PWM gate signal.

OPTO COUPLER

The ACPL-W346 is ideally suited for driving power SiC MOSFETs used in this prototype. In general the gate of a MOSFET is made active by switching 10 - 12 V and rapidly switched off using -5 V. DC0-DC converters for the gate signal interface provides the +12 / -5 power supply and the opto coupler connects the MOSFET gate to this power supply with an interface opto-coupler.

DC-DC CONVERTER

The DC-DC converter G1212S-2W is used which is specially designed for applications where an isolated voltage is required in a distributed power supply system. The DC voltage of ±12V is given as the input to the opto-coupler ACPL-W346 in the design.

HIGH POWER MOSFET

Switching times range from tens of nanoseconds to a few hundred microseconds, depending on the device. MOSFET drain source resistances increase as more current flows through the device. Power MOSFETs can be paralleled in order to increase switching current and therefore overall switching power. Nominal voltages for MOSFET switching devices range from a few volts to a little over 1000 V, with currents up to about 100 A. Here two MOSFET devices are used for switching purposes called as S1 and S2.S1 is used to drive the positive half cycle, S2 is used to drive the negative half cycle.

EMBEDDED CONTROLLER

The Emcraft systems[5] SOM-BSB (system-on-module -baseboard) provides designers with a prototyping platform for SmartFusion2 system-on-chip (SoC) FPGAs, which integrated with inherently reliable Flash based FPGA fabric [1], a 166 MHz ARM Cortex-M3 processor, advanced security processing accelerators, DSP blocks, SRAM, eNVM and industry-required high-performance communication interfaces all on a single chip.

The Emcraft system called embedded controller is designed to generate the 16 step PWM control signal using a verilog coding [6].
Steps to generate the PWM control signal
It controlled by the two input switches namely

a) SW1 → System on and system off
b) SW2 →Power up and down

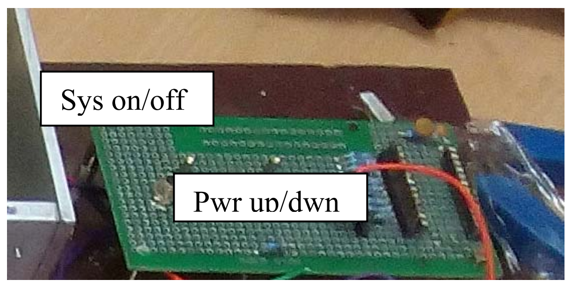

Figure-4. sys on/off and power up/down.

a) Initially when the system is powered and the SW1 is OFF, then the reset signal is given.
b) When the system on or SW1 is ON and a default power up or SW2 is OFF, then a maximum frequency is given to the system.

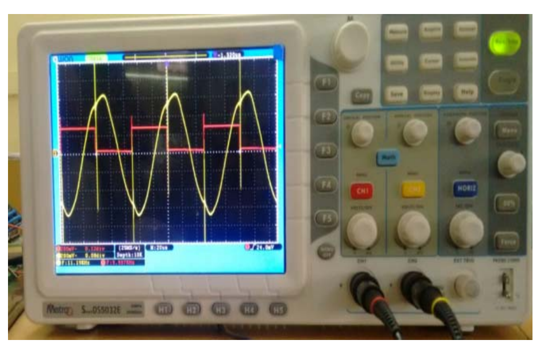

Figure-5. MOSFET current waveform at low power mode.

c) When the power down or the SW2 is ON, then the minimum frequency is given to the system.

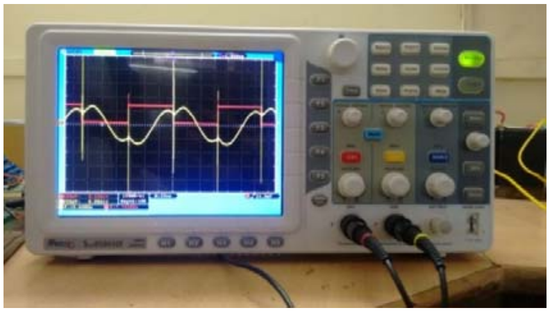

Figure-6. MOSFET current waveform at high power mode.

d) Two modulated signal is generated called
i) Positive processing cycle

The PWM controlling signal produced for the positive half of the sine wave

ii) Negative processing cycle

The PWM controlling signal is inverted to produce the negative half of the sine wave

e) The dead time of 1.0us is added to both the positive and negative processing cycle.

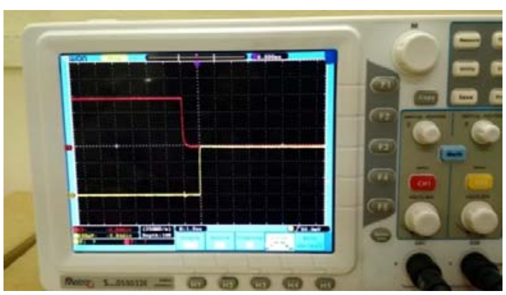

Figure-7. Dead time for the reduction of short circuit.

f) Four output is from the Embedded controller namely

a. The positive processing signal(pos_pls)
b. The negative processing signal(neg_pls)
c. The positive dead time(add_pulse_pos)
d. Negative dead time(add_pulse_neg)

These control signals are given as input to the MOSFET gate driver circuit through which the modified sine wave can be obtained.

FERRITE CORE TRANSFORMER

At high frequencies eddy current losses will acquire, because they have a tendency to vary with frequency square. For high frequency in the range of kHz, the laminated core cannot be used and only the core made of ferrite materials must be used. Ferrite is the best choice in high frequency transformer except for mechanical ruggedness.

USE OF LITZ WIRE IN THE TRANSFORMER

The higher transmission efficiency can be obtained by using the litz wire [7]. The litz wire can operate with frequencies up to 2.8 MHz. It is designed to reduce the proximity effect losses in conductors used at higher frequencies during the power transmission as shown in the Figure-8.

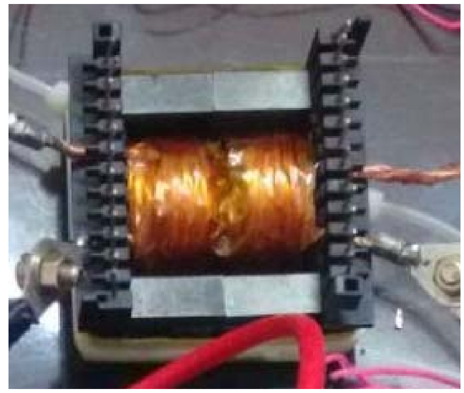

Figure-8. Ferrite core transformer with litz wire wounded.

WORKING OPERATION

The power supply of 230V ac input is given to MCCB (molded case circuit breaker) where sine wave is generated which is used as a circuit protection for short circuits and overload conditions. The 230v AC voltage is reduced to +/- 48V level connected with line reactor which forms a LC circuit and it serves to filter out spikes of current and may also reduce injection of harmonic currents into the power supply. This +/- 48 V DC supply and given as input to the main inverter MOSFET switch board. The inverter MOSFET Bridge can operate in a wide range of voltages ranging from 24V DC -600V DC and it will increase the switching current and switching power. Two MOSFET switches for PWM based power transfer are realized by a suitably generated gate pulses are given to each switch in accordance with the developed pattern to obtain the desired output. It is also used for switching on-off power at high frequency (~50 kHz) can directly pulled from the embedded controller which is operated at low voltage DC source. The PWM signal S1 is given as input to drive the MOSFET1, the PWM signal S2 is given as input to drive the MOSFET2.The MOSFET switches between the two signals under certain tuning conditions that causes the current to "free-wheel" through the internal diodes of the MOSFET devices, as one MOSFET turns off and the other device turns on. If MOSFET1 is conducting when the MOSFET2 device is switched on, then a "short circuit" occurs. In order to avoid the short circuit condition a dead time is given. The dead time is the period at which no part of an H-bridge driver or MOSFET driver is turned on. The alternating power signal thus generated goes through step-up transformers to produce a higher voltage signal. The output of the step-up transformers then gets rectified and filtered by capacitors to produce a high voltage DC supply. The primary part of the transformer

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core is connected to the charging head which is placed underwater and the secondary part is in the underwater vehicle and the magnetic coupling is realized when the secondary part or the pick-up head is brought to the vicinity of the charging head that has the primary part of the transformer and corresponding voltage is stored in the battery in the charging unit.

RESULTS AND DISCUSSIONS

In wireless charging system, the high frequency of 10khz and high power of 500W is achieved by generating voltage across magnetic coupling unit called a ferrite core transformer as shown below in the Figure-9 is built for the underwater vehicle that can operate under the variable environmental conditions and keeping the marine eco system intact.

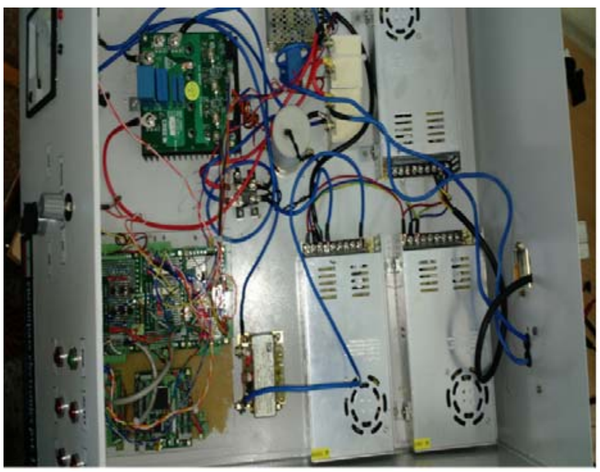

Figure- 9 wireless charging system.

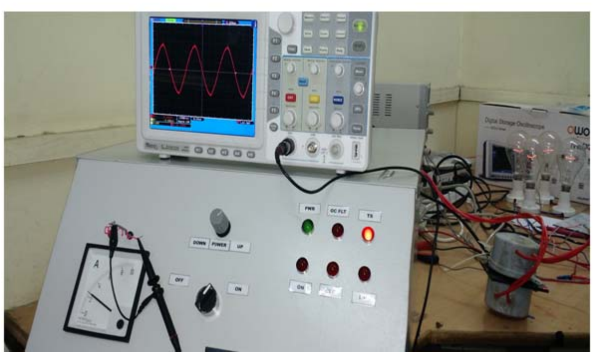

Figure-10. Wireless charging system testing and connected along with the ferrite core transformer.

FUTURE ENHANCEMENT

The underwater vehicle are now being used with additional tasks with more roles and missions constantly evolving by the development of more advanced processing capabilities and high yield power supplies. Hence this system can be enhanced by creating a control system which can operate to produce variable power generation based upon the need of the applications like military applications, SONAR, GPS, communication related applications etc.

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