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Design of a High-Efficiency Wireless Power Transfer System for Electrical vehicle battery charging system using DSMPI controller

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Abstract: *In this paper a wireless power transfer system for electric vehicle battery charging is proposed. The battery charging takes place through high frequency transformer fed from single phase AC input power supply. The AC power supply is converter to DC using DBR and the DC voltage is controlled using PFC Zeta converter for maintaining the power factor of the input source. In order to improve the power transfer efficiency. The resonant tank of the proposed system is designed to operate the converter as a current source and as a voltage source at two different frequencies to implement the constant current (CC) mode charge and constant voltage (CV) charge, respectively. Both the CC and CV modes adopt PI controller for controlling the duty ratio of the switches in the primary side of the high frequency transformer. The control on the duty ratio of these switches controls the output voltage at the terminals of the battery henceforth controlling the charging battery current. The PI controller is further updated with DSM-PI controller with improved response time making the controller to work faster stabilizing the current of the battery at a faster response rate.*

Keywords: Constant current (CC)/constant voltage (CV) charge, electric vehicles (EVs), wireless power transfer (WPT), zero phase angle (ZPA), PI Controller, DSMPI Controller.

1. Introduction

The charging protocol defined as required quantity of current or voltage for how much period of time and the process there after completion of charging, depends on the battery size and its type. Some type of batteries hold high tolerance towards over charging (a fully charged battery subjected to continued charging) and by connecting it to a constant voltage or current source it can be recharged. Towards charge cycle's end simple chargers must be disconnected manually, whereas a different kind of battery type uses a time in order to cut off the charging current at a fixed time, roughly when charging is completed. There even exists other battery types that cannot withstand over-charging and gets damaged, over heated or explodes. A charger possibly will have voltage or temperature sensors and a microprocessor controller that securely adjusts the charging current & voltage and determines the terminal cut off point. A trickle charger comparatively gives a smaller amount of current that is adequate to compensate for self-discharge of a long time idle battery. Slow battery chargers need hours to get completely charged. High-rate chargers fastly restore most capacity, but some battery types may not be able to tolerate it. These kinds of batteries may require active monitoring in order to protect it from overcharging. Electric vehicles ideally are in need of high-rate chargers. A good battery charger provides durable and high performance batteries. Chargers have a low priority in the price-sensitive market and often get the "after-thought" status. Battery and charger goes hand in hand like a horse and carriage. Cautious planning provides high priority to the power source and is placed at the beginning of the project rather than after the completion of hardware, as is a common practice.

1.1 Electric Vehicle Battery Charger

The latest year problem is of the "range anxiety" that is associated with the electric vehicles (EVs) that has been increased by the introduction of hybrids (HEVs) and plug in hybrids (PHEVs) and the development of higher energy density batteries which are capable of storing maximum energy in the same space. With the growing esteem of electric vehicles, "range anxiety" is now taken over by "charging anxiety". The solutions not only involves the development of chargers but also the design and implementation of a network of private and public charging stations with related user confirmation and billing systems, the negotiation of international standards and developing the electricity grid to carry the high load, public safety and planning issues. These issues are not answerable in a single line. On one side, national and international standards organizations try to find best solutions to these issues and on the other hand commercial enterprises try to leapfrog the competition by looming new and unique innovative solutions to distinguish their offerings. Some of these issues are explored here.

1.2 Battery Charging

A battery is said to be discharged when its voltage dips than the cut-off voltage or when the battery state of charge is below 20 percent and this is the point when battery needs to be recharged. Over-charging and over-discharging of a battery can affect its condition significantly. Therefore developing a proper battery charging method is a vital part. The method of battery charging is based on precise battery evaluations for state of charge (SOC), state of health (SOH) and temperature. The appropriate battery charging method assists in efficient battery charging from the initial to the final SOC battery state, and also protects the battery from overheating, extending its life span and improving capacity consumption.

2. Introduction of Wireless Power Transmission

Wireless power transmission also termed as Wireless Power Transfer (WPT), Wireless Energy Transmission (WET) or Electromagnetic Power Transfer is the process of transmission of electrical energy without the use of wires as a material link. In this an electrically driven transmitter device generates a time-varying electromagnetic field that is transmitted to a receiver that extracts power and supplies to the load.

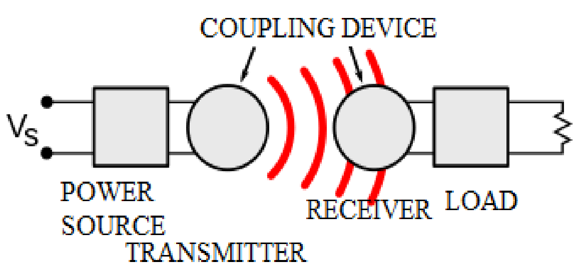

Fig 1 Block Diagram of Wireless Power Transfer System

Wireless power transfer is a basic term for a number of diverse technologies for transmitting energy by means of electromagnetic fields. Wireless power transfer techniques are classified into two categories, namely near field and far-field.

2.1 Battery Electric Vehicles (BEV)

Battery Electric Vehicles (BEV) usually called EVs, are fully electric vehicles with rechargeable batteries and without gasoline engine. Electricity is stored onboard with high-capacity battery packs and its power is used to run the electric motor and all onboard electronics. They do not emit any harmful emissions and hazards as that of traditional gasoline-powered vehicles. Electricity from external source is used for charging BEVs. Based on speed of charging classification of Electric Vehicle (EV) is done.
The classifications are Level 1, Level 2, and Level 3 / DC fast charging. Level 1 EV charging makes use of standard domestic (120v) outlet to plug in the electric vehicle and usually takes over 8 hours to charge an EV for approximately 75-80 miles and usually takes place at home or workplace. Level 1 charger has the capability to charge most EVs in the market. [10]
Level 2 charging uses a specialized station that provides power at 240v and are usually present at workplaces and public charging stations and takes about 4 hours to charge a battery for a range of 75-80 miles.
Level 3 charging, DC fast charging, or fast charging is presently the fastest charging solution provided in the EV market which are found at dedicated EV charging stations and usually charge a battery for a range of 90 miles in about 30 minutes.

2.2 Plug-In Hybrid Electric Vehicle (PHEV)

Plug in Hybrid Electric Vehicles can recharge the battery using either regenerative braking or plugging in to an external electrical power source. While the standard hybrids at low speed can travel about 1-2 miles before the assistance of gasoline engine, PHEV models can cover range from 10-40 miles before the assistance of gas engines.

2.2 Hybrid Electric Vehicles (HEV)

HEVs are powered by gasoline as well as electricity. The electric energy being generated by the car's own braking system so as to recharge battery and is termed as 'regenerative braking', i.e. a process in which the electric motor helps to slow the vehicle speed and uses some of this energy which is normally converts to heat by brakes.
HEV starts off using the electric motor and then subsequently gasoline engine comes into action with the

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rise of load or speed. An internal computer controls this action and ensures the best economy for the driving conditions.

Because of the link capacitor the full charged battery must not be switched rapidly to system (Motor and AC/DC) as the high inrush current can damage the capacitor therefore the link voltage should be raised steadily by making use of a pre-charge switch that is in series to a pre-charge resistor. After pre-charging intermediate circuit, the main switch excluding pre-charge resistor of the battery can be closed.

2.3Advantages of Electric Vehicle Battery Charger

- No fuel, no emissions
- Low Running costs
- Low maintenance
- Performance
- Popularity

2.4 Zeta Converter

In present scenario DC/DC converters are widely used as power supply in electronic systems. Zeta converter forms a major source of this part. It is a fourth order DC/DC converter that is capable of amplifying as well as reducing the input voltage levels without inverting the polarities. The main reason for this is the presence of capacitors and inductors that act as a dynamic storage element. It is also a nonlinear system which can be seen as a buck-boost-buck converter with respect to output and boost-buck-boost converter with respect to the input.

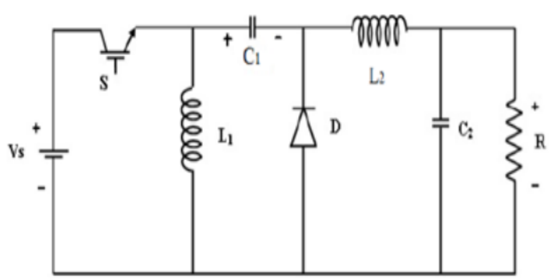

Fig. 2 Basic Zeta converter circuit

The above figure depicts the basic non isolated zeta converter. Based on the value of inductance, capacitance, load resistance and operating frequency there can be different operating modes. We can make use of state space analysis method for continuous inductor current. Following assumptions are made for this method: -

1. Converter operates in continuous inductor current mode
2. switching devices are considered to be ideal
3. Frequency ripples in DC voltages are neglected

Modes of Operation of Zeta Converter

The following are the two modes in which a Zeta converter works.

Mode 1: Charging Mode

- switch is ON
- Diode D is off
- the inductors L_1 and L_2 draws current from voltage source V_s

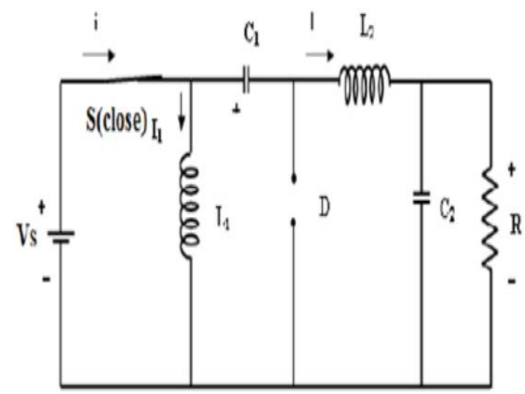

Fig.3 Mode 1 equivalent circuit

Mode 2 : Discharging Mode

- Switch is OFF
- Diode D is ON
- The energy stored in inductor L_2 is transferred to R(load)

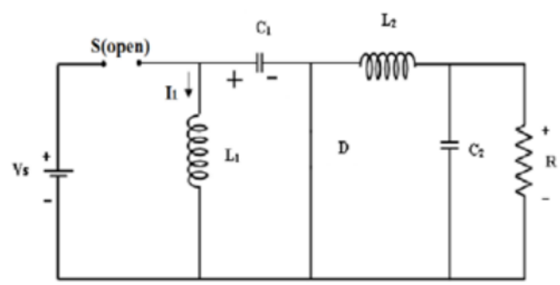

Fig.4 Equivalent circuit of mode 2

3. Proposed Model

This dissertation mainly deals with the modeling of the Wireless Power Transfer System for electrical vehicle battery chargers. Figure 5 shows the proposed model of the dissertation that shows the main parts of the system like the inverter, rectifier and the resonant tanks that mainly consists of power electronic devices.

The main component of the battery charger is the high frequency transformer whose primary side is fed via a single-phase ac power supply. A DBR is used so as to convert the ac supply to DC. As shown in the figure this

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DC voltage is fed to the zeta converter that helps to maintain the power factor of the input source.

The resonant tank consisting of two intermediate coils and the resonant capacitors helps in improving the power transfer efficiency by increasing the overall magnetizing impedance between the transmitter & receiver coils with no ferrites. It also aids the converter to operate as a current source by implementing constant current mode charge and to operate as a voltage source by implementing constant voltage charge.

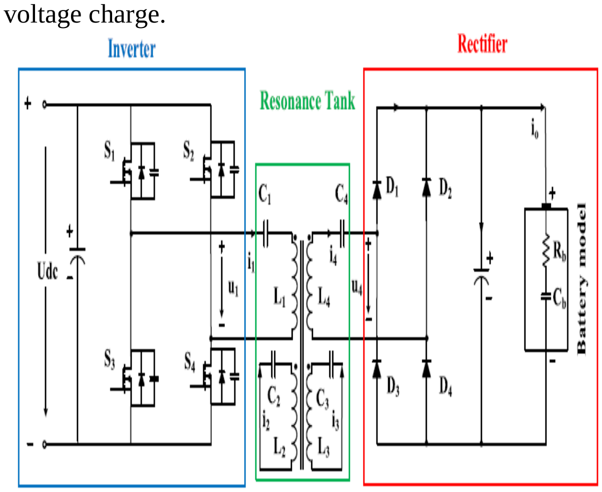

Fig.5 Wireless Power Transfer System

During each mode of charge operations i.e. the CC mode or the CV mode the converter operates at a fixed frequency and aids in soft switching of the switching devices and zero phase angle condition can be achieved easily.

The main role of the PI controller is to control the duty ratio of the switches present at the primary side of the high frequency transformer which results in the control of the output voltages at the battery terminals thereby controlling the charging battery current.

The inclusion of the DSM PI controller in place of PI controller along with the above features also improves the response time of the controller that helps in faster control and stabilization of current of the battery hence improving the response time.

3.1 Updation of Proposed Model Using DSM PI Controller

Sliding mode control is a nonlinear control that has properties like robustness, accuracy and simple implementation. The two main benefits of sliding mode control are

i. The dynamic behavior of system can be modified by choosing a particular sliding function.
ii. The response of the closed loop becomes entirely insensitive to particular uncertainties.

3.2 Conventional Sliding Mode Control

The SMC theory has been widely applied in linear and nonlinear systems, engineering control problems etc. The SMC method provides an efficient approach to solving control engineering problems. By establishing a sliding mode to the control of a system, stabilization and disturbance rejection can be achieved.

The conventional PSMC is of a proportional type that forces system states to slide into the preset sliding surface, and finally reaches the origin of the phase plane. When the state-trajectory slides on the sliding surface, the analogous dynamic performance of the system is ruled by the equations of sliding surface. Hence, the PSMC has a tough robustness adjacent to external disturbances and uncertainties.

There are two key prerequisites for the PSMC. One to design a sliding surface after which the states are imposed to slide into the sliding surface by the control law based switching. Two, each tracking points on the sliding surface must fulfill the sliding conditions. The switch of the control law is decided by the predefined switching conditions. The control switch, guides the trajectory into the region restricted by boundary layers. Based on the sliding conditions, the trajectory steadily moves onto the sliding surface and advances to the target point.

3.3 PI Sliding Mode Control

The sliding surface of the PISMC consists of two sliding surfaces, the proportional sliding surface and the integral sliding surface, respectively. It provides more parameters with which the controller can be tuned and it reduces undesirable effects due to the external disturbances effectively.

3.4 DSM-PI Control

The conventional PI controller has the gains fixed at one particular value. Whereas in DSM-PI controller gain values are frequently changed according to the error generated. DSM-PI controller is used to obtain current signal from speed error input. It continuously monitors the proportional and integral gains respectively and as a result the response time is minimized.

A PI controller has proportional K_p and integral K_i gains fixed at a particular value, that remains constant for both higher value or lower value of error. While in DSM-PI controller the values of gains K_p and K_i are uneven with respect to the error generated. If the error in voltage or current is high, value of gains K_p and K_i are amplified and if it is low the gain values are reduced in order to reduce the settling time.

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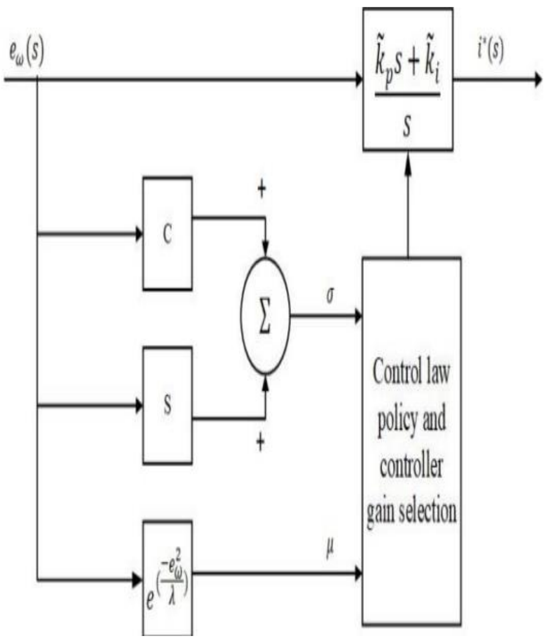

Fig.6 DSM-PI Control Scheme Block Diagram

The main advantage of this DSM-PI Control scheme is that the settling time of the speed-time response is decreased with reduction in disturbances and oscillations and this helps in faster control and stabilization of current of the battery hence improving the response time.

4. Simulation Result and Discussion

The complete design related to the project is created in MATLAB & Simulation using Sim Power System Toolbox and also the analysis of the different MPPT Technique. This designing is conducted in two stage stages: -

1. Simulation of a High-Efficiency Wireless Power Transfer System for Electric Vehicle with PI controller
2. Simulation of a High-Efficiency Wireless Power Transfer System for Electric Vehicle with DSM-PI Controller

4.1 Result Analysis

The figure 7 shows the simulation model of the proposed topology. The power supply form a single phase AC source of 230V 50Hz is taken as input. The diode bridge rectifier converts the input AC voltage into variable DC voltage which is further connected to PFC Zeta converter for DC voltage stabilization.

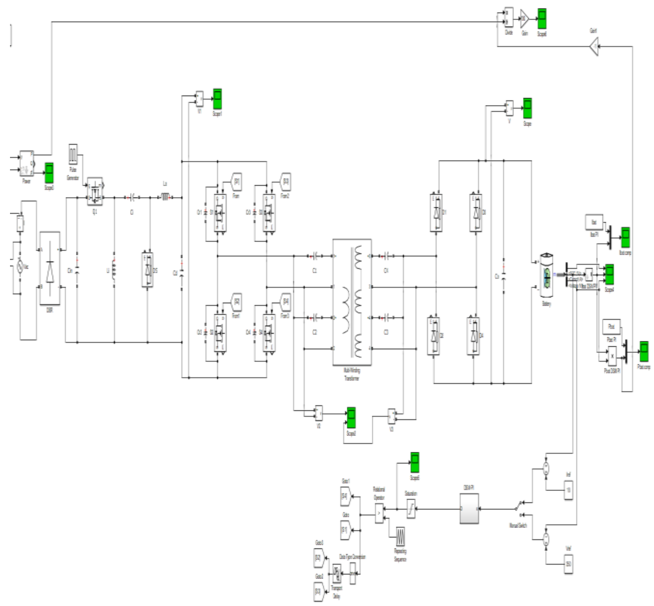

Fig.7 Proposed topology with DSM-PI controller

Figure 9 shows the internal structure of variable K_p (proportional gain) and K_i (integral gain) values that varies with changes in the error input. The DSM-PI gain controller changes the values of K_p and K_i and makes the controller react faster to the changes. Thereby, the output voltage of the converter also settles faster in comparison with conventional controllers.

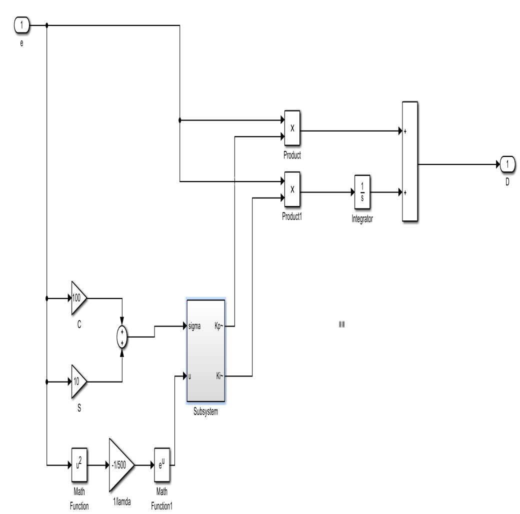

Fig.8 DSM-PI controller internal structure

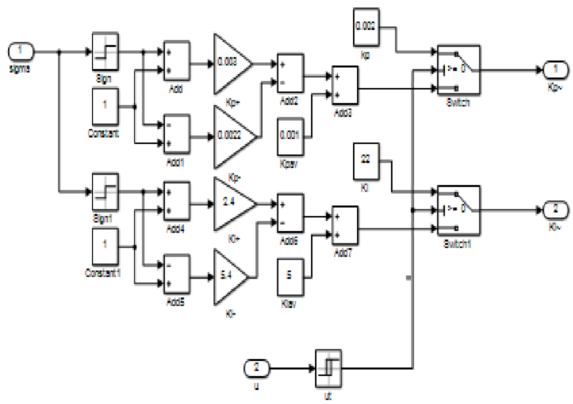

Fig. 9 Variable Kp and Ki gains

Figure 10 showcases the power factor of the input AC source that is maintained at 0.97 during the charging of the battery through the converter topology. This power factor is maintained by the PFC Zeta converter that is connected to the DBR. Figure 11 shows the DC voltage output of the Zeta converter that settles at 500V during the simulation of 1sec.

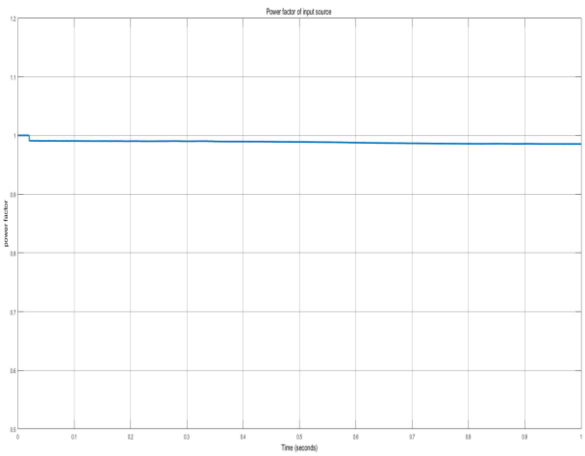

Fig.10 Power factor of input source

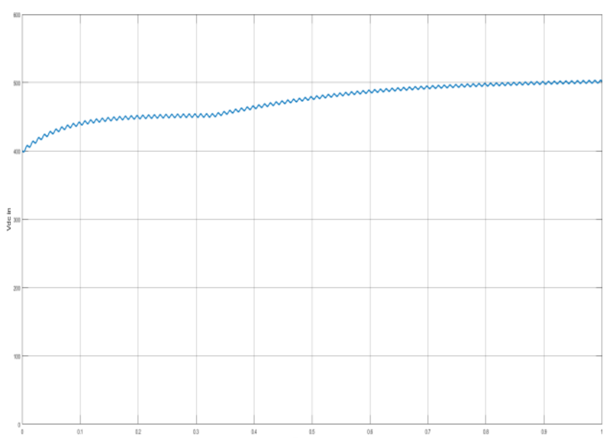

Fig. 11 DC input voltage to the high frequency converter

Figure 12 shows comparison of battery charging current and power consumption of battery during charging with PI and DSM-PI controller. It can be inferred from these graphs that the current and power settles faster in case of DSM-PI as compared to that of PI controller.

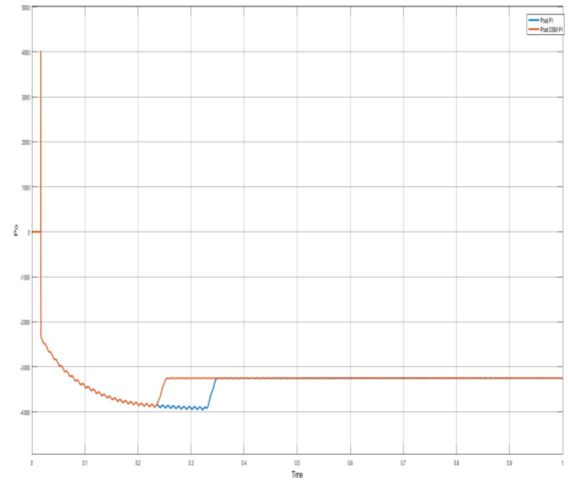

Fig.12 Battery power consumption comparison with PI and DSM-PI controller

5. Conclusion

From the above obtained comparison results we can infer that the battery charging current as well as the power of the battery settles faster with DSM-PI controller as compared to that of PI controller. The improved coupling factors, along with the help of two additional intermediate coils, are the reason behind the high efficiency of the proposed converter. It is possible for the proposed converter to achieve the ZPA condition and soft switching in both the CC and CV modes over the entire charge operation. Also, the proposed WPT system can implement the CC and CV mode charges at a fixed resonant frequency.

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