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Design of Sliding Mode Controlled Bi-directional DC-DC Current Source Resonant Converter for an Inductive Contactless Battery Charging Application

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Abstract*: The practical use of current source DC-DC resonant converters has an outstanding performance in terms of its robust and fast performance. In this paper, the non-linear behavior during the battery charging application is solved using an adaptive Sliding Mode Control (SMC) technique. The SMC has a robust feature in fast transient responses over large load disturbances. The proposed converter uses Contactless Energy Transfer (CET) system that provides a suitable reactive power compensation for the design. The winding parameters of the inductance are mathematically modeled with low coupling factor to remove the voltage and current harmonics. The designed converter is subjected to input side perturbation for a non-linear disturbance and the output obtained using the Sliding Mode Controller is analysed. The non-linearity at the output voltage is reduced when using the SMC. The controller design show the setting time of the DC voltage under such disturbance is reduced to 97%. The proposed system is mathematically modeled and simulated using MATLAB/Simulink. The prototype model is designed and the results are analyzed.

Keywords*: Contactless energy charging, energy transfer, harmonics, resonant converter, transfer function model.

I. INTRODUCTION

In recent research, the inductive contactless energy transfer system (CET) is widely used in large power charging applications, electric vehicles etc. This system is designed as a two coil system parameterized with alternating currents having 20kHz above. This magnetic coil is designed with optimal number of turns in the winding inductance L_1 and L_2 maintaining the co-efficient of coupling (k) for reduced effect of harmonics in both voltage and current. Contributing to the proposed system, the CET is applied to a bi-directional dc-dc current source resonant converter (CSRC). In traditional method, the design features are limited to wireless energy transfer. With the improved design of input impedance and voltage transfer function, the proposed converter is readily applied in the CET system.

The DC drives used in the industries are very sensitive to the speed and torque variations. For such applications the speed and the torque are to be maintained as per the desired output requirement. Small perturbations can occur at unfortunate conditions either in the input side or in the output load side. Such perturbations are observed to be non-linear. These non-linear disturbances have greater effect that will affect the motor load output. The load side disturbances have common solutions over the period of research. However, the input side non-linear disturbances have a greater effect and the point of providing a solution to it is a greater challenge. These disturbances are though rare to occur, have to be controlled to very high sensitive level. The well-known study of Sliding Mode Control (SMC) [1]-[3] is very commonly applied to the non-linear variations. In the proposed method, the SMC is used under such non-linear input perturbations for the drive system. The variations in the speed are earlier observed for the system which is reduced to a minimum value by using the SMC. The modelling and design of the controller is successfully applied and the results are verified.

II. MODELING OF PROPOSED BI-DIRECTIONAL CSRC CET SYSTEM

A. State-Space Model of bi-directional CSRC

The state space model of a bi-directional current source resonant converter is shown in the figure 1. The state space model expression of the proposed converter can be expressed as a variable u as shown.

$$\frac{di_i}{dt} = \frac{1}{L_i}\left[V_i - u\left(\frac{1+\mathrm{sgn}\,v_c}{2}\right)V_c\right] \qquad (1)$$

$$\frac{di_L}{dt} = \frac{1}{L_r}V_c \qquad (2)$$

$$\frac{di_0}{dt} = \frac{1}{L_0}\left[\left|V_c\right| - v_0\right] \qquad (3)$$

$$\frac{dV_c}{dt} = \frac{1}{C_r}\left[u\left(\frac{1+sngv_c}{2}\right)i_i - i_L - i_0\,\mathrm{sgn}(v)_c\right] \qquad (4)$$

$$\frac{dv_0}{dt} = \frac{1}{C_0}\left[i_0 - \frac{v_0}{R}\right] \qquad (5)$$

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where i_i is the input current variable, v_c and i_L are the resonant state variables, and v_0 and i_0 are the output filter state variables. In addition, u is the output signal of the control system which is a discrete-time variable. This signal determines the operational mode of energizing or de-energizing. For simplicity, to derive this model, all components are assumed ideal and no parasitic effects have been considered in this paper.

B. Operation of proposed bi-directional resonant converter

The mode of operation is classified in two stages, (i) energizing and (ii) de-energizing stages. The switching techniques are so defined such that the duty cycles are slightly higher than half to achieve the soft switching modes [7]. The voltage and the current stress are there by eliminated during conduction. The figure 1 shows the modes of operation of the proposed circuit.

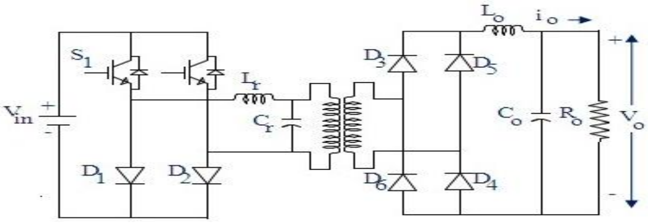
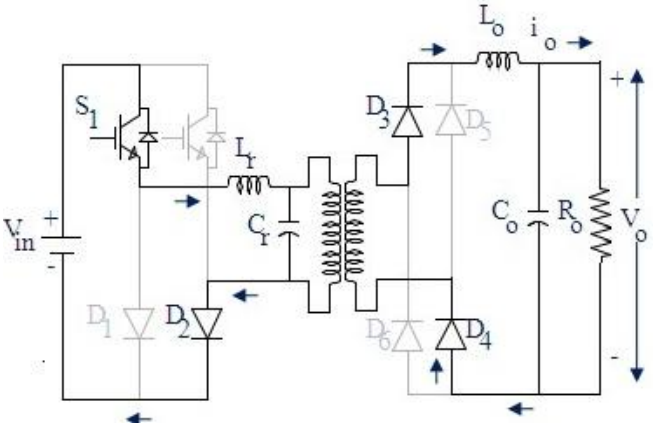


Fig. 1. Proposed current source resonant converter

Positive Energizing mode (0<t<T/2): During the positive energizing mode, the resonant capacitor (C_r) is supplied by positive current that charges the output capacitor (C_0) continuously. The figure 2a shows the positive energizing modes. The switches S_1 and S_2 are switched *ON* at *t=0* and the current flows through S_1, L_r, D_3, R_0, D_4, S_2 thus charging C_0. The output voltage v_0 is positive and allows the battery to charge fast with a capacitor voltage v_c > 0. The switch S_1 and S_2 are turned *OFF* and the load is disconnected from the supply. The resonant capacitor C_r start to discharge and the current continues to charge the output capacitor (C_0) under continuous conduction mode.



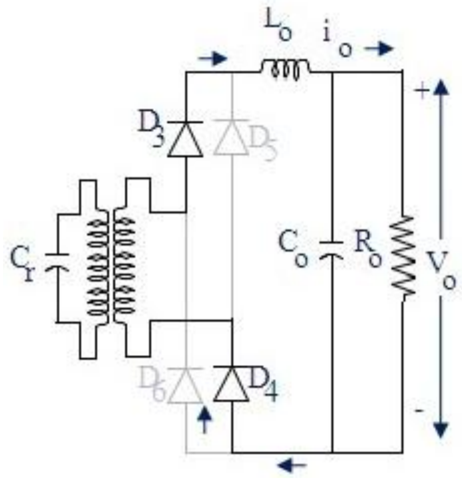


Fig. 2(a). Modes of operation – Positive energizing mode

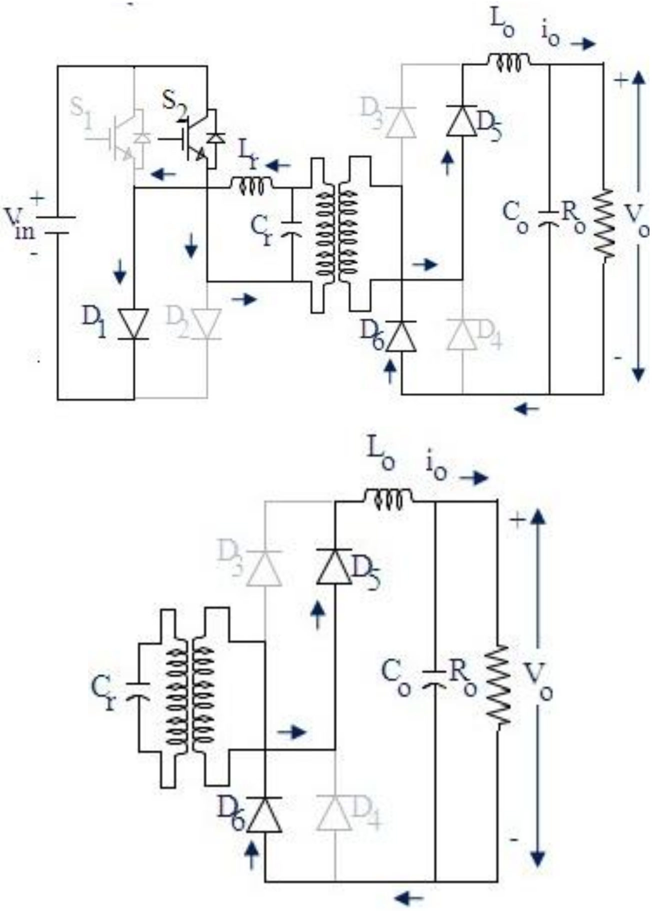


Fig. 2(b). Modes of operation – Negative energizing mode

Negative Energizing mode (T/2<t<T): During the negative energizing mode, the resonant capacitor (C_r) is charged through the negative current. The figure 2b shows the negative energizing modes. The switches S_3 and S_4 are switched *ON* at *t=T/2* and the current flows through D_2, S_4, R_0, S_3, D_1, thus charging C_0 continuously. The output voltage v_0 is positive and allows the battery to charge fast with a capacitor voltage v_c > 0. The switch S_3 and S_4 are turned *OFF* and the load is disconnected from the supply.

The resonant capacitor C_r start to discharge and the current continues to charge the output capacitor (C_0) under continuous conduction mode. The figure 2b shows the switching technique applied for the proposed converter.

III. MODELING OF CONTROL SCHEME

Sliding Mode Control (SMC) is predominantly used for the non-linear control of any system. The control stability and the robustness add major advantage to various power electronic applications like battery charging, motor speed control etc. The proposed system uses the SMC for the stable and robust output for the battery charging application though the bi-directional resonant converter.

SMC works on the reference of the sliding surface where the trajectory should be brought as close near to the sliding surface for better output performance. The major components or the elements considered for the design of SMC includes, hitting condition, existing condition, and stability condition. The hitting conditions are the trained limits of the existing condition that are made achieve the stability condition under simultaneous operation of the controller.

The sliding surface is the reference set for the desired output of the system. Here, in the battery charging application, the output voltage and the current under the contactless design of the power modulator is considered control element. The trajectory element should hit the sliding surface irrespective of the input conditions, load disturbances or any other conditions that might be responsible to disturb the system stability during the operation. However, the switching values are responsible to generate the hitting conditions. Logically the switching function is given as,

$$f = \frac{1}{2}\left(1 + sign(\Delta)\right) \tag{6}$$

where, Δ is the instantaneous state variable and Δ=0 is the sliding surface of the system.

The state variables are designed from the error values of the capacitor voltage and the inductor current that can be expressed as,

$$x_1 = v_{ref} - v_{C_1} \tag{7}$$

$$x_2 = i_{ref} - i_{L_1} \tag{8}$$

From the above equations the linear combinations of these state variables can be expressed as,

$$\Delta = \delta_1 y_1 + \delta_2 y_2 = HX \tag{9}$$

Where δ_1 and δ_2 are the sliding coefficients and H is the vector of the sliding coefficients. Therefore the state-space can be written in standardize form as below,

$$\dot{X} = AY + Bf + D \tag{10}$$

Where

$$A = \begin{bmatrix} 0 & \frac{1}{c} \\ -\frac{1}{L} & 0 \end{bmatrix},\ B = \begin{bmatrix} \frac{2i_L - i_{DC}}{c} \\ \frac{v_{C_1} + v_{C_2}}{L} \end{bmatrix},\ D = \begin{bmatrix} \frac{i_{DC} - i_{ref}}{c} \\ \frac{v_{in} - v_{ref}}{L} \end{bmatrix} \tag{11}$$

The existing condition is ensured after hitting the sliding surface and approaches towards the equilibrium point. The modeling of the inequality approaching towards the equilibrium point cam be derived as,

$$\dot{S}_{s\longrightarrow 0+} = GAX + GBu_{s\longrightarrow 0+} + D < 0$$
$$\dot{S}_{s\longrightarrow 0-} = GAX + GBu_{s\longrightarrow 0-} + D > 0$$

Presuming constant values of inductor L and capacitor C.
The actual values of the proposed network parameters L and C are used in the above equation of inequality, for verification. From the above equation, for a range of practical values of v_{in}, such that the proposed converter is configured in boost mode, the inequality condition will be satisfied. The compliance of minimum value of input voltage is required for the abidance of the existence condition. The values of sliding coefficients are calculated from the above equations. The sliding mode controller design for the proposed method is shown as in the figure 3.

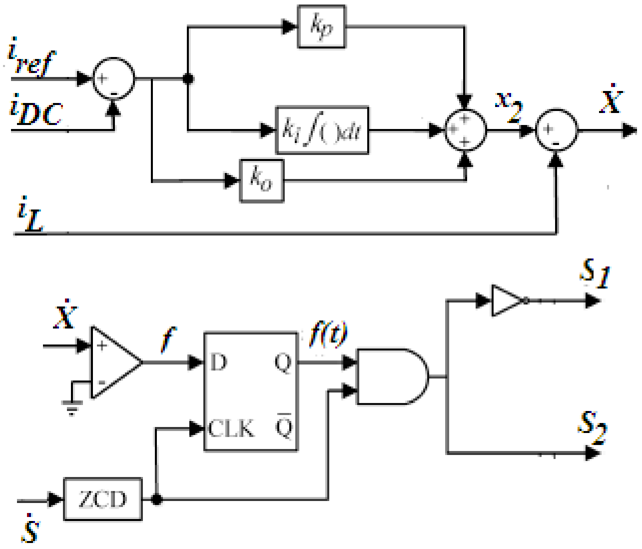


Fig. 3. Proposed Sliding Mode Controller Design

IV. MODELING AND SIMULATION OF THE PROPOSED METHOD

The proposed bi-directional current source resonant converter is mathematically modeled to charge a 45V battery. The model is subjected to the input voltage disturbance and the non-linear behavior of the system is analyzed.

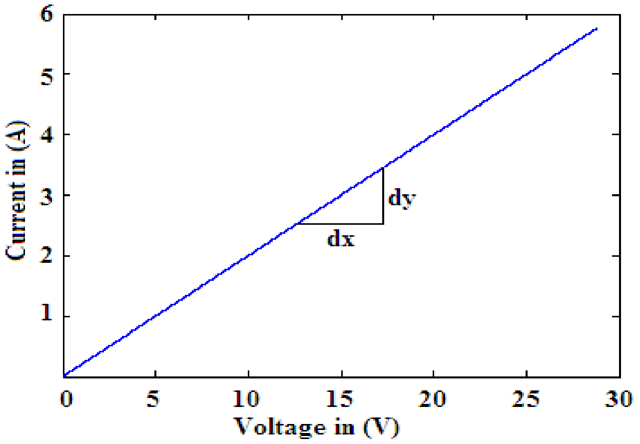


Fig. 4. I-V Characteristics of the proposed converter

The SMC is mathematically modeled in MATLAB is made to control the non-linear input condition to charge the battery with no interruption. The proposed work simulation is confirmed from its operative characteristics in I-V curve. The figure 4 shows the I-V curve which forms the slope, s=dy/dx. The current source resonant converter is switched at a higher frequency of 20kHz. The pulse generated to the converter switches are self-commutated with no lap over and the switching losses are less. However, the contactless power transmission increases the induction current at the output level. The figure 5 shows the pulse generated for the switches S_1 and S_2 respectively.

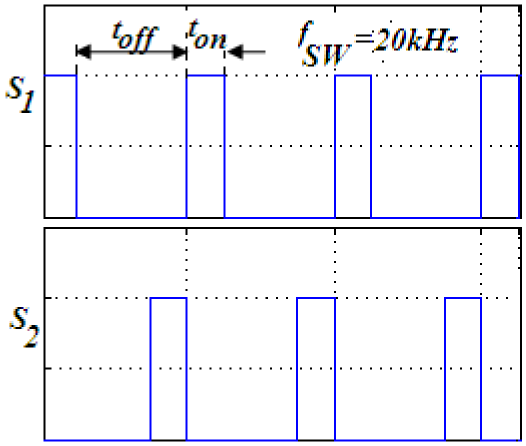


Fig. 5. Gate pulse applied to the proposed converter

The open output voltage of the converter for the battery charging unit is shown in the figure 6. The 12V battery is allowed to charge for 120 minutes to obtain the complete charging cycle. The proposed simulation model shows the voltage is regulated and no disturbance is considered at the input side. The open voltage for the linear model obtained is approximately equal to 11.5V at ideal condition.

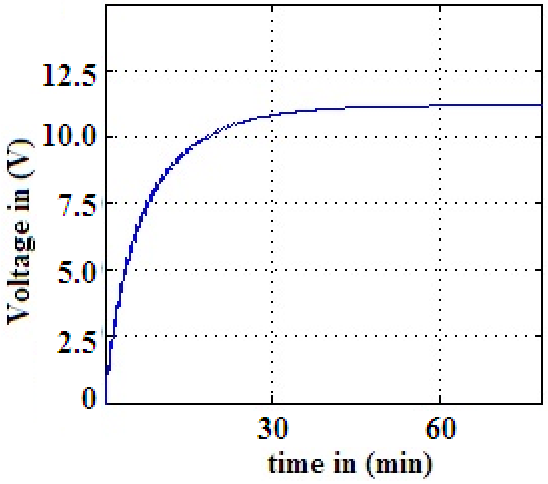


Fig. 6. Open voltage at the input terminal for the battery charging

The 12V battery connected to the current source resonant converter is subjected to an input voltage side perturbation. The system is subjected to a no-linear disturbance is observed to have a large voltage ripple at the output side. Such disturbance causing non-linearity is controlled using the sliding mode controller (SMC). The sliding mode controller observes the variations and the parameters have eliminated the non-linearity change at the output. This produces a regulated output voltage for the charging application. The figure 7 shows the output voltage with and without SMC.

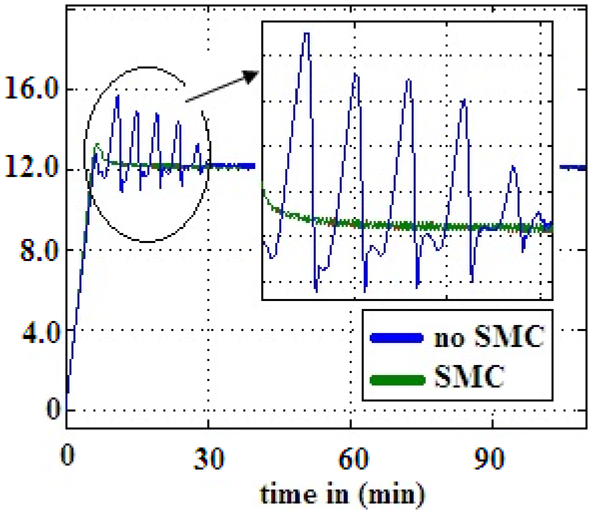


Fig. 7. Output voltage obtained with and without SMC

Table- I: Conditions without and with SMC

Conditions	Steady state conditions	Transient Conditions	
		Without SMC	With SMC
Charging battery voltage (V_{bat})	45 V	45 V	45 V
Output Voltage (V_o)	12 V	11.5 V	11.5 V
Charging period	120 min	180 min	125 min
Switching frequency (f_s)	20kHz	20kHz	20kHz
Transient time	-----	2 min	2 min
% Voltage stress	-----	25 %	21.5 %
Efficiency (%)	-----	67 %	97 %

In Table 1, the conditions for steady state and transient conditions under SMC and without SMC is explained. The conditions are analyzed for charging the battery voltage (V_{bat}), output voltage (V_o), charging period, switching frequency, transient time, percentage of voltage stress and efficiency. It is noted that the efficiency 97% is reached by using the Sliding Mode Controller. The battery charging period is also reduced thereby the voltage stress is reduced to 21.5%.

V. RESULTS AND DISCUSSIONS

The proposed work is mathematically modeled for a non-linear battery charging system. A 12V battery is used to power a Contactless Energy Transfer dc/dc converter that is tested under a steady state condition. The open voltage is measured to have a regulated 11.5V for the battery of 12V design. According to the design parameters considered during the mathematical modeling, a tolerance of ± 5% is taken. The battery charging at steady state condition is normal and the setting time to a complete the charging takes about 2 hours. The converter is operated with a switching frequency of 20 *k*Hz. The system observed to have a very linear characteristic. A small perturbation is assumed and the system is tested under the transient condition.

It is observed that the system losses its linearity and the efficiency reduce to 67% allowing 25% of stress level across the converter switches. This non-linearity is overcome by the Sliding Mode Controller (SMC) which when applied gives a greater efficiency of 97%. Also, the voltage stress across the switches is reduced by 3.5%. The modeling of the SMC has also reduced the battery charging time to 125 minutes from 180 minutes during the transient period. The adaptive nature of the SMC has improved the converter design for the battery charging applications.

VI. CONCLUSION

The current source resonant converter with a contactless structure is used in the proposed design. The system is analyzed and tested for linearity during the steady state condition. The slope s, is found to be linear for any value of dy with respect to dy. The objective of the proposed method is reached by setting a non-linear disturbance at the input side having to experience a small perturbation. This disturbance that affects the output voltage in its amplitude and setting time is reduced using the SMC. The SMC is designed by considering current source applied at the input level. The SMC generates a well-defined duty cycle to operate the converter to produce a constant output. The SMC reduced the voltage stress to a value of 1.5% as of the steady state condition. The setting time of the voltage to charge the battery to the regulated value is also reduced to 97%. The improvements over the effects in the system both at steady state and the transient conditions using the sliding mode controller are discussed. On the other hand the on-time variation can also be reduced using artificial intelligence to have a control on the stability.

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