

Model of Power Electronics Used for Electric Vehicles Contactless Charging

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Abstract— This paper deals with power electronics used in contactless power transfer (CPT) and its operational functions modelled in FEM analysis software. Equations for computing basic CPT transformer parameters are mentioned in first chapter. In second chapter a CPT system modelled in multiphysics software Simplorer Ansys is proposed. Proposed model consists of CPT transformer and power electronics necessary to ensure transfer capability. The main part of the paper deals with system output voltage ripple reduction and its impacts.

1. CONTACTLESS POWER TRANSFER

Contactless power transfer means electric energy transfer between two galvanically unconnected devices which is based on electromagnetic induction. CPT consists of functional blocks shown in Figure 1.

Energy from AC line is transformed to high frequency (HF) waveforms which is transferred by CPT transformer and then transformed to DC current and stored in electric vehicle batteries. This paper deals with power electronics used in CPT to create needed current and voltage waveforms for energy transfer and store. There are many conditions on power electronics operational parameters. Equations listed below refer about some of them.

1.1. CPT Transformer

CPT transformer is basic part of contactless power transfer where energy is transferred between two air coils with large gap. CPT transformer equivalent scheme is shown in Figure 2(a).

Active power value transferred by CPT transformer is given by Equation (1):

$$P_2 = \frac{\omega_0 M^2 Q_S}{L_2} I_2 [W] \quad (1)$$

where $Q_S = P_2/S_2$ is quality factor of secondary transformer side and ω_0 is resonant operational angle velocity.

CPT transformer impedance Z is given by Equation (2):

$$Z = \frac{(\omega M)^2 + (R_1 + j\omega L_1)(R_L + R_2 + j\omega L_2)}{R_L + R_2 + j\omega L_2} [\Omega] \quad (2)$$

CPT transformer efficiency η is:

$$\eta = \frac{R_L}{(R_L + R_2) \left(1 + \frac{R_1(R_L + R_2)}{(\omega M)^2}\right) + R_1 \left(\frac{L_2}{M}\right)^2} [-] \quad (3)$$

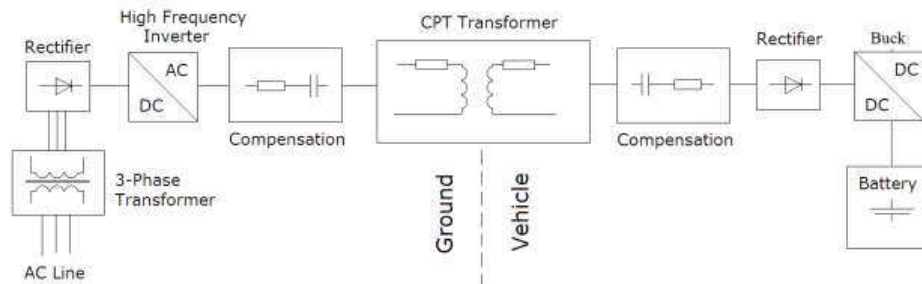


Figure 1: CPT functional blocks.

By condition $\frac{R_1(R_L+R_2)}{(\omega M)^2} \Rightarrow 0$, the maximal CPT transformer efficiency is given by Equation (4):

$$\eta_{\max} = \frac{R_L}{R_L + R_2 + R_1 \left(\frac{L_2}{M}\right)^2} [-] \quad (4)$$

1.2. CPT Capacitive Compensation

Due to CPT transformer operates at high frequency, CPT has high impedance, transfers high reactive power value and CPT efficiency is low. To decrease values of reactive power and impedance, CPT has to be compensated. There are a basic CPT capacitive compensation scheme — series-series compensation SS shown in Figure 2(b).

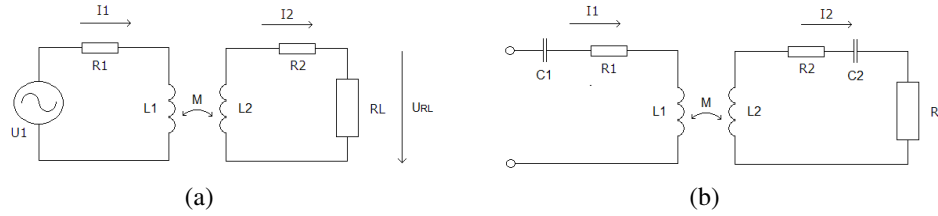


Figure 2: (a) CPT transformer equivalent scheme, (b) series — series capacity compensation SS.

The capacitive compensation in secondary winding is used to increase transferred reactive power value. So the whole system has to operate at resonant velocity angle ω_0 . The secondary capacitive compensation value is given by Equation (5):

$$C_2 = \frac{1}{\omega_0^2 L_2} [F] \quad (5)$$

Primary capacitive compensation parameters for series-series connection are given by Equation (6):

$$C_1 = \frac{C_2 L_2}{L_1} [F] \quad (6)$$

Transformer with series — series compensation and secondary resonance frequency 100 kHz was modeled in Simplorer. Figure 3(a) shows dependence phase shift between source voltage and current on frequency. At frequencies below resonance the phase shift corresponds with capacitive character of impedance. At secondary resonance frequency, inductances are fully compensated by capacities. As seen in Figure 3(b), where depicted waveform of apparent and active power, system is has highest transfer capability. With increase of frequency above resonance, inductive character of impedance grows and transfer capability diminishes.

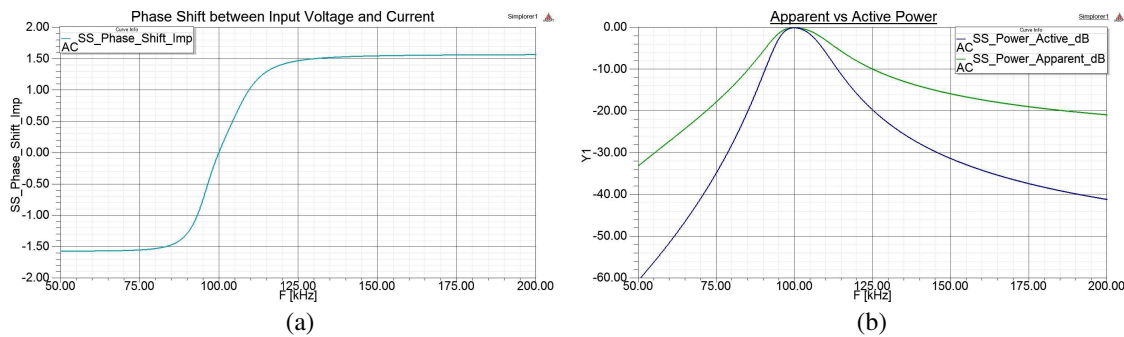


Figure 3: (a) Phase shift between input voltage and current, (b) apparent versus active power.

2. CPT POWER ELECTRONIC MODEL IN SIMPLORER ANSYS

In Figure 4 is depicted CPT system used for simulations. CPT system is comprised of following components: Input three phase grid (1), input uncontrolled rectifier (2), HF inverter (3), air-core

Table 1: Simulated system parameters.

Parameter	Value	Parameter	Value	Parameter	Value
V_{GRID}	400 V_{RMS}	LaSS	100 μH	R2SS	0.04 Ω
CF_IN	10 mF	LbSS	8.9 μH	CF_HF_OUT	10 μF
C1SS	23.8 nF	MSS	6.5 μH	RLSS	2.5 Ω
C2SS	164.4 nF	R1SS	0.13 Ω	f_0	100 kHz

transformer with series-series compensation (4), HF rectifier (5) and load (6). Simulated system parameters are summarized in Table 1.

System level semiconductor models are used for simulation of input rectifier (2), HF inverter (3) and HF rectifier (5). Inverter's (3) MOSFETs are simultaneously switched in pairs MOS1, MOS2 and MOS3, MOS4. The pairs are controlled by two PWM signals with frequency equal to secondary resonance frequency, duty cycle 0.5 and same amplitude (high level = 5, low level = 0). The PWM signals are shifted by half period and they are subtracted from each other in order to forestall short-circuit in an inverter branch.

CPT transformer with voltage ratio of 2 : 1 is simulated as equivalent circuit of mutual inductance and two leakage inductances. For compensation is used series — series topology described in Section 1.2. Compensation capacitor values are calculated according Equations (5) and (6) for secondary resonance frequency 100 kHz.

Main focus of the simulations described in this paper is output voltage ripple and its reduction, thus load (6) is modeled as pure resistance.

$$RC = \frac{V_{pp}}{V_{RMS}} \cdot 100, [\%] \quad (7)$$

3. OUTPUT VOLTAGE RIPPLE REDUCTION AND ITS IMPACTS

One of the important parameters describing system quality is output voltage ripple. This output voltage ripple is measured in steady state at load resistance. Output voltage ripple is caused by ripple at input rectifier (2) and ripple at HF rectifier (5). Ripple of DC voltage for inverter (3) is given by grid, type of rectifier (in this case is used three-phase full bridge uncontrolled rectifier) and filter capacitor value. DC voltage ripple frequency is 300 Hz (grid frequency (50 Hz) multiplied by number of rectifier pulses (6)). Ripple coefficient RC is calculated by Equation (7), where V_{pp} is voltage peak to peak value and V_{RMS} is voltage RMS (root mean square) value.

Dependence of DC voltage ripple coefficient on by input rectifier (2) filter capacitor (CF_IN in Figure 4) can be seen in Figure 5(d). For modeling the capacity value 10 mF was picked, which corresponds to ripple coefficient 2.53%.

As seen from Figure 5(c), after reaching steady state, DC voltage and its ripple forms the upper waveform envelope of HF rectifier output voltage. Ripple with frequency 200 kHz (resonance

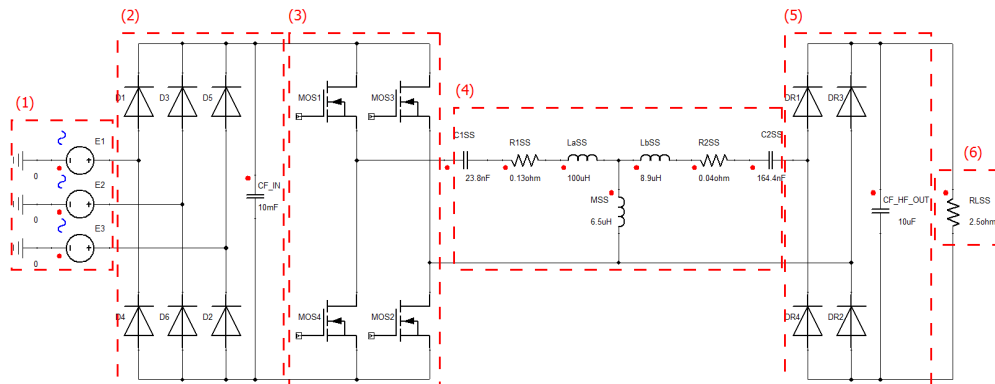


Figure 4: Simulated CPT system.

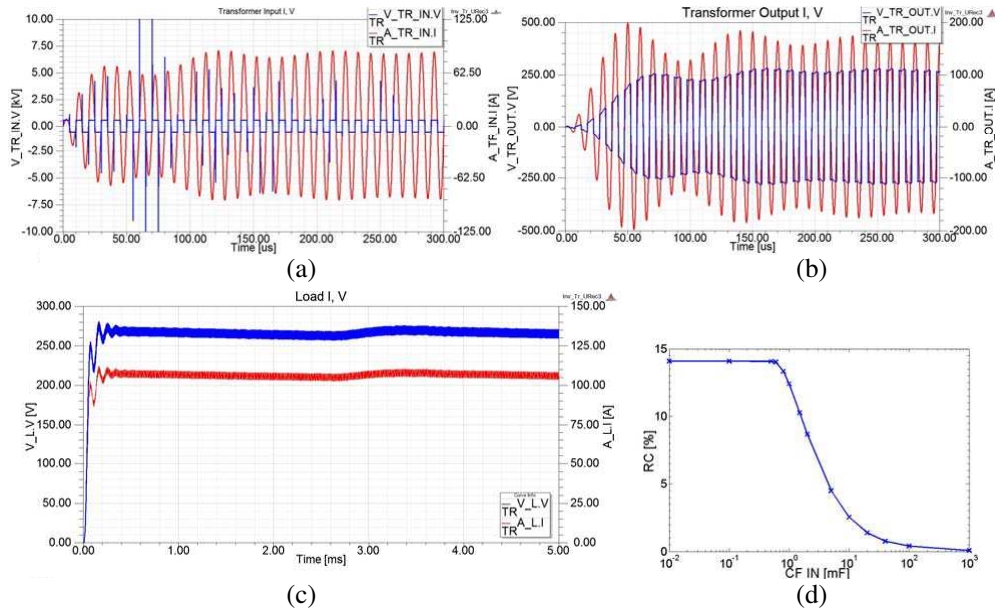


Figure 5: Current (red) and voltage (blue) waveforms at (a) transformer input, (b) transformer output and (c) load. (d) Input rectifier voltage ripple in dependence of filter capacitor value.

frequency (100 kHz) multiplied by number of rectifier pulses (2)) is caused by HF rectifier (5) and it can be limited by increasing rectifier's filter capacity (CF_HF_OUT in Figure 4). However, large capacity has two adverse effects: Firstly, rectifier filter capacitor causes transient state at beginning of CPT system operation. With capacity increase the transient state duration is also increasing. Secondly, rectifier filter capacity affects resonance circuit constituted by CPT transformer and its compensation. This effect is apparent from oscillations of load voltage waveform during transient state, and from deformation of voltage waveforms measured at both input and output of CPT transformer (Figures 5(a), (b)). In transition state voltage spikes with size up to 12 kV emerges at inverter MOSFETs. This spikes may be potentially cause voltage breakdown of MOSFETs and shorten device lifespan. Current waveform is only slightly deformed and remains very close to sinusoid with changing amplitude.

Figure 5 illustrates influence of HF rectifier capacitor size on transformer output voltage waveform. When no capacitor is used, voltage is sinusoidal (Figure 6(a)). However, single phase rectifier without filter capacitor isn't convenient for desired operation. With increasing capacitor value, waveform has rectangular shape with superposed sinusoid (Figure 6(b)). With further capacitor value increase, sinusoid component perishes and voltage is purely rectangular (Figure 6(c)).

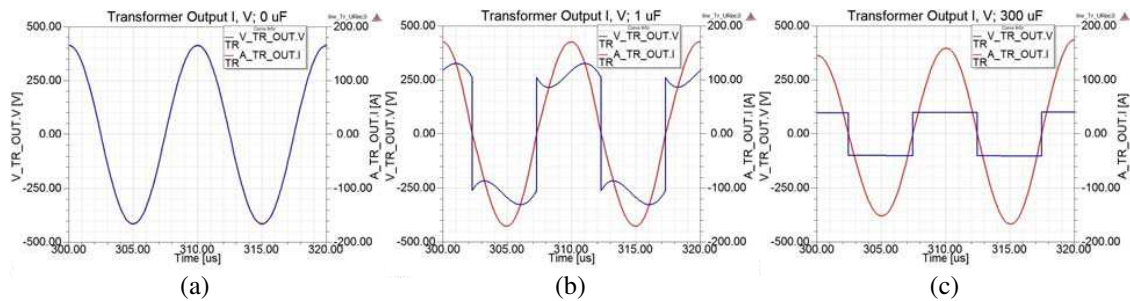


Figure 6: Influence of HF rectifier capacitor size on voltage and current waveforms at transformer output.

In steady state the change of capacity has no influence on transformer output current waveform, which remains sinusoidal. Transformer electromagnetic noise is dependent on current waveform. Sinusoidal current causes lowest electromagnetic noise. Thus increase of filter capacity doesn't cause increase of electromagnetic noise radiated by CPT transformer.

4. CONCLUSION

In first chapter the fundamental equations describing CPT transformer are summarized and series — series capacitive compensation topology is explained. In second chapter CPT system model for simulations in Simplorer software is presented. Described CPT system model will be used for further simulations and improved in order to increase simulation accuracy. Third chapter concern itself with causes of system output voltage ripple. It also deals with ripple reduction by use of filter capacitors and with impacts of reduction by filter capacitors on voltage and current waveforms.

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