Converters with Energy Dosing for Charging of EV's Li-ion Batteries

Nikolay Madzharov [1], Goran Goranov [2]

Abstract - **The scientific and the applied problems treated in the present paper are related to the development of a DC/DC power supplies with energy dosing for charging of electrical vehicles (EVs) batteries. They are a hybrid between the achievements in modern microelectronic components - frequency capabilities and low commutational losses, and the trends in the development of power conversion circuits which maintain the power or/and current constant and independent from the battery state operating of charge (SOC).**

Some converters are presented together with their modifications. Theirs operation principle has been pointed out, as well as the investigations that have been carried out. Conclusions have been drawn about the possibility of obtaining good charging characteristics when the battery parameters change during the different charging scenarios.

Keywords – **Converter, Energy dosing, Battery, Electrical vehicles, Battery state operating of charge.**

I. INTRODUCTION

The power electronic topologies for high power battery chargers can be largely classified into two categories: single phase types and two phase types [1,3,9,12]. Single phase battery chargers generally combine the power factor correction stage and the DC-DC conversion stage into one. They can be more efficient than the two phase types. However, single phase type battery chargers have a low frequency ripple in the output voltage and as a result, the switch and transformer ratings become larger [1,7,12]. The two phase types generally use a boost type converter to improve the power factor at the first stage and a DC/DC converter for the control of the voltage, current and power at the second stage. Two phase power converters use their own controllers to control the input current and the output voltage, respectively power, at the same time. They have a higher power factor and a lower harmonic distortion i.e., they have an advantage that there is almost no low frequency ripple in the output.

The other main characteristic of the charging power supplies is their universality regarding the battery parameters and good regulating possibilities. Not with standing the progress made, the methods used to regulate the output voltage of power sources, are not sufficiently smooth and envisage the use of relatively complex matching transformers, capacitors and ect.

With a view of solving the problems in this area, DC, converters with energy dosing (ED) have been synthesized analysed and tested [1,2,9,12]. According to ED method of operation, they generate, with a specified power, an output voltage corresponding to the particular parameters of the battery [1-3].

The main purpose of the present paper is also in this direction - presentation of circuits of power supply with ED for battery charging and the preliminary investigation performed on them.

A 32 kW battery charger is implemented to demonstrate the stability and performance of the system with ED. The validity of the concept is then verified through the constant current (CC) mode and the constant power (CP) mode charge of an actual Li-ion battery.

II. DC CONVERTERS WITH ENERGY DOSING DEVELOPED FOR EV CHARGERS

The EV battery, such as electrical load, is characterized with strongly variable parameters during changing process - from idle running to short circuit. In table 1 are presented parameters of tested EV battery (Fig.1a) that contains more than a hundred pieces of AMP20m1HD-A single battery (Fig.1b), production of A123 Systems [9]. In connection with this, the charging convertor should have specific characteristics – on one hand to be able to limit and support output current and on the other hand to provide the dynamic feeding of the necessary power to the battery.

a) b)

Fig. 1. Tested EV battery

A great number of circuits of DC/DC converters with ED are known [1,2,4-12]. Their distinctive feature is the presence of a dosing capacitor included in series in the battery loop through the interval of energy consuming by the mains. All of them provide dosing of the energy supplied to the battery, reliable work of loads changing and high commutation stability in the dynamic operating mode.

In table 2 are showed the basic circuit and respective time charts, illustrating the principle of converters with ED operating mode. It can be seen that the dosing capacitor voltage is fixed always to the value of the supplying DC

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voltage. Consequently, at constant work frequency the power given in the battery will always be one and the same. For the circuits with combined recharge of the dosing capacitor, in the expression for the power takes part the coefficient ***K*** which is less than 1 and depend on the load parameters.

TABLE I
PARAMETERS OF EV BATTERY

Energy	18.7kWh (67.32MJ)			
Battery capacity	56.7 Ah			
Output voltage	310 ÷ 374V DC			
Charging current	60 ÷ 90A DC			
Internal resistance	0.10 ÷ 0.14Ω			
Battery voltage U_{DCbat},V	**310**	**330**	**350**	**374**
I_{DCbat} = 60A **R_{BAT}** [Ω]	5.17	5.50	5.83	6.23
I_{DCbat} = 75A	4.13	4.40	4.67	4.99
I_{DCbat} = 90A	3.44	3.67	3.89	NA

The DC converters with ED have the following advantages [1-4, 6, 7, 11, 12]:

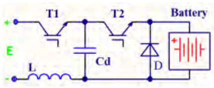
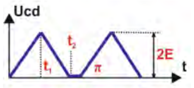
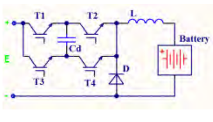
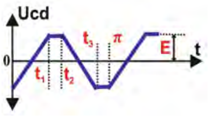
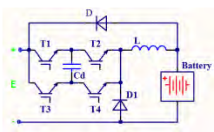
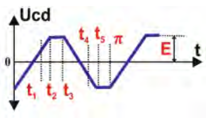
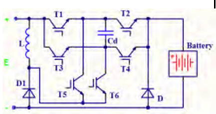
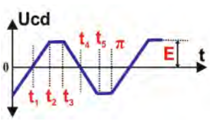
-wide range concerning the load parameters and power;

-good regulation characteristics at satisfactory for the practice range and sensitivity;

-with the enlarging of the regulation depth the conditions for steady and optimum commutation of the transistors are kept, i.e. the switching is ZCS and/or ZVS;

-good electromagnetic compatibility with the mains.

TABLE II
DC/DC CONVERTERS WITH ENERGY DOSING

<table>
<tr><th>Circuit</th><th>Method of ED</th><th>Intervals</th></tr>
<tr><td colspan="3">1) DC/DC converters with ED and capacitor recharging by load current</td></tr>
<tr><td>
</td><td>
</td><td>$0 \div t_1$ T_1
$t_1 \div t_2$ T_2
$t_2 \div \pi$ D
$\mathbf{P=E^2C_df}$</td></tr>
<tr><td>
</td><td>
</td><td>$0 \div t_1$ T_1, T_3
$t_1 \div t_2$ D
$t_2 \div t_3$ T_2, T_4
$t_3 \div \pi$ D
$\mathbf{P=E^2C_df}$</td></tr>
<tr><td colspan="3">2) DC/DC converters with ED and combined recharge of the dosing capacitor</td></tr>
<tr><td>
</td><td>
</td><td>$0 \div t_1$ T_1, T_3, D
$t_1 \div t_2$ T_1, T_3
$t_2 \div t_3$ D_1
$t_3 \div t_4$ T_2, T_4, D
$t_4 \div t_5$ T_2, T_4
$t_5 \div \pi$ D_1
$\mathbf{P=kE^2C_df}$</td></tr>
<tr><td>
</td><td>
</td><td>$0 \div t_1$ T_1, T_6
$t_1 \div t_2$ T_1, T_3, T_6
$t_2 \div t_3$ D, D_1
$t_3 \div t_4$ T_4, T_5
$t_4 \div t_5$ T_2, T_4, T_5
$t_5 \div \pi$ D, D_1
$\mathbf{P=kE^2C_df}$</td></tr>
</table>

Depending on the operating characteristics, the circuits of DC converters with ED can be systematized in the following groups:

-by the way of dosing capacitor recharging - combined or by the battery current;

-by the principle of output voltage regulation;

-by the presence of preparatory capacitor recharging;

-by the amount of the output impulses for one work frequency period – single-cycle and two-cycle circuits.

The comparative analysis of the results from the examinations and the obtained characteristics [2-4] give the possibility that the following recommendations for the usage of the shown in table 2 circuits can be formulated:

-at the lack of requirements to the battery current pulsations it is expedient to be used the circuits from group 1.

-at the necessity of supporting small output current pulsations, at a wide regulation range are used the circuits with combined recharging of the dosing capacitor. Theoretically, they do not have limits in the regulation characteristics;

-a DC/DC converter, combining ED and transforming, take a medial place in comparison to the examined circuits. To keep the small output current pulsations at a range of regulation K>3 it is necessary a great increasing of the commutation inductance value.

The dosing source in the shown DC/DC converters with ED is a capacitor, because of its great energy reserve and easy realization. It is also possible the use of inductance or inductance-capacitive circuit, tuned to the working frequency.

II.I. NON SYMMETRICAL DC/DC CONVERTER WITH ENERGY DOSING

Figure 2 presents a non symmetrical DC/DC converter with ED.

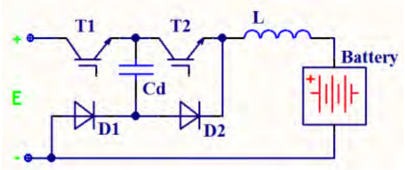


Fig.2. Non symmetrical DC/DC converter with ED

Control pulses are passed from the control system to T_1, T_2. In case of a battery load the circuit operating principle is as follows. When transistor T_1 is forward - biased, current flows along the circuit (+)E,T_1,Cd,D_1,L,battery,(-),E. When the dosing capacitor is charged up to voltage equal to E, the diode D_2 is forward - biased and the current is closed along the circuit D_2, D_1, L, battery.

By the forward-biasing of T_2 the capacitor Cd, charged up to the supply voltage E, begins discharging through T_2, L, battery, D_1, Cd. When the dosing capacitor is discharged the energy stored in the load is closed along circuit D_2, D_1, L, battery.

The expression

$$W = Cd.E^2/2 \ , \qquad (1)$$

is valid for the energy which is stored and given up by means of the dosing capacitor. Taking into consideration the fact that the amplitude of the capacitor charge Cd for one half-period is equal to the supply voltage Ucd=E, the power given up in the load can be determined

$$P = Cd.f.E^2 , \tag{2}$$

where Cd is the capacitance of the dosing capacitor, f - the operating frequency of the dosing device (T_1,T_2,Cd), E - the supply voltage.

II.II. SYMMETRICAL DC/DC CONVERTER WITH ENERGY DOSING

Figure 3 presents a symmetrical DC/DC converter with ED having a decoupled dosing capacitor.

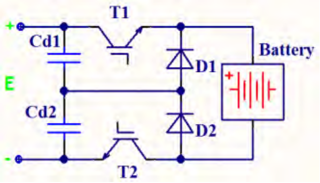


Fig. 3. Symmetrical DC/DC converter with energy dosing

The control pulses are passed from the control system to transistors T_1 and T_2. In the first half-period T_1 is forward - biased, and current flows along the circuit T_1, battery, D_2, Cd_1, the capacitor Cd_1 gets discharged and Cd_2 charged to voltages 0 and E, respectively. The total sum of the dosing capacitors Cd_1 and Cd_2 voltages is always equal to the voltage of the supply source E. When the dosing diode D_1 gets forward - biased the energy consumption from the supply source stops. The current flows along circuit D_1, battery, D_2. After T_2 gets forward-biased the current flows along Cd_2, D_1, battery, T_2 and Cd_2 gets discharged and Cd_1 charged. After that the dosing diode gets forward-biased, and the current flows along circuit D_1 - battery - D_2.

The output power in the load is determined from the expression

$$P = (C_{d_1} + C_{d_2}).f.E^2 , \tag{3}$$

where Cd_1 and Cd_2 - capacitance of the dosing capacitors, f - operating frequency of the dosing device, E - supply voltage.

The first conclusion that can be drawn from the expressions for W and P is that when the working frequency, the input voltage and the dosing capacitors value are unchanged, the power transmitted to the battery is constant and does not depend on the battery parameters. Supporting constant power means that the output convertor voltage is matched with the battery voltage.

The second special feature of the converter is obtained by replacement the battery current expression $I_{out} = U_{out} / Z_L$ in (2) and (3). After some transformations it is obtained a correlation giving the connection between the output and the input voltage.

$$U_{out} = 2E\sqrt{\frac{C_d.Z_L}{2.T}} \tag{4}$$

The conclusion which can be drawn is that by changing the work frequency the output converter voltage, respectively battery voltage can be supported constantly when the battery parameters and/or the input voltage are changed. In figure 4 it is shown the dependence of the output voltage in function from the frequency at different loads (battery parameters). The information from these characteristics is used for converter designing, as it gives an account of the connection between the load value and the capacitor Cd value, giving the power on one hand, and the dependence of the output voltage on the frequency and the input voltage, on the other hand.

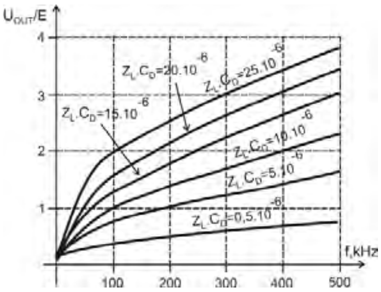


Fig 4. Regulation characteristics

The supporting and the regulation of the output voltage are realized by a feedback which changes the converter working frequency. The analytic dependence of the regulation law can be obtained as the expression for the output power is differentiated in relation to the time t. After some transformations

$$U_{out}I_{out} = 4C_d E^2 f \ , \tag{5}$$

$$U_{out}\, di_{out} + I_{out}\, du_{out} = 4C_d E^2\, df \tag{6}$$

using the expressions

$$du_{out} = di_{out}(Z_L // 1/\omega\ C_F) \tag{7}$$

and

$$I_{out} = U_{out} / Z_L \ , \tag{8}$$

is obtained

$$\frac{du_{out}}{df} = 2E\sqrt{\frac{C_d Z_L}{2f}}\,\frac{1}{1+\omega C_F Z_L/2} \ . \tag{9}$$

This expression is the operating function of the control system and gives the law, by which it should be modified the frequency of changing the load parameters with a purpose of supporting of constant output voltage. Using this function the control system can foresee, define, compensate and obtain the needed converter output characteristics.

III. EXPERIMENTAL INVESTIGATIONS

The experimental research has been performed using non symmetrical and symmetrical DC converters with ED from figures 2 and 3, having power P=32 kW and frequency f=20 kHz. In fact they belong to the group of converters with ED and capacitor recharging by load current and have all characteristics, defined in paragraph II.

Figures 5 and 6 are presented both studied modes of battery charge at two values of the charging power, respectively current, till the charge level SOC = 90%, when the process ends. The initial points in two characteristics starts from SOC=10% and SOC = 50% level of charge.

At the beginning of the process of charge (0-500 sec) the DC converter with ED maintain constant power and gradually increase in the current value from $0.8xI_{DC}$ to reach I_{DC}, 500sec after the beginning of the process. The battery voltage could be calculated by following relationship:

$$U_{BAT\ f} = U_{BAT_{90\%}} - I_{DC}.R_{BAT} = [(0{,}9.(374-310)) + 310] - I_{DC}.R_{BAT} \tag{10}$$

where $U_{BAT\ f}$ -is battery voltage after end of charging scenario.

The parameter $U_{BAT\ 90\%}$ is battery voltage at SOC = 90%.

On reaching this value the control system sends a signal to the DC convertor with ED for finish the process of charge.

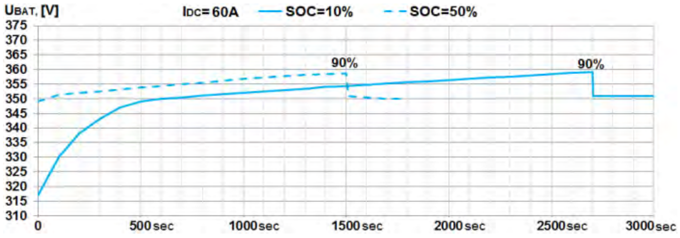


Fig.5. Charging scenario at charging power 21 kW (I_{DC} = 60A) and SOC 10 and 50 %.

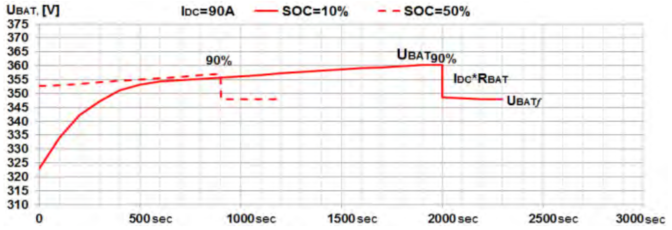


Fig. 6. Charging scenario at charging power 31 kW (I_{DC} = 90A) and SOC 10 and 50 %

From the tests implemented can be concluded that the charging source works most efficiently while maintaining maximum charging current or/and output power. Depending on the type of battery used, there is a maximum value of SOC, in which the charging process can be carried out – typically SOC = 80 ÷ 90%.

The obtained from the circuit analysis expressions and tests results allow to be drawn charging characteristics at different batteries. They define the area in which the converter with ED can support constant output current or/and power.

IV. CONCLUSION

This paper described the design, control and tests of a DC converter with ED, which can be used to charge the Li-ion battery bank of EVs. A 32 kW converter was designed and implemented to verify the validity of the developed operating mode of ED and control algorithm. The obtained expressions for the control system operating function giving the law for operating frequency changing with a purpose to keep the output power constant when the battery parameters are changed. It has been verified that in ED mode algorithm the charging converter works most efficiently and maintaining maximum charging current or/and output power. It can be concluded that the developed converters with ED may contribute to higher system efficiency and a longer battery life due to its lower ripple current characteristics.

On the basis of the performed analysis and tests the following advantages of the discussed circuits can be pointed out:

a) possibility for operation with almost constant power and/or current and different loads;

b) operation in modes close to idle running and short circuit;

c) transistor commutation with zero current and zero voltage;

d) easy algorithm of transistors operation;

e) high power factor in relation to the mains.

The following disadvantages can be pointed out:

a) high maximum values of the currents through the transistors and the diodes;

b) a large number of active and passive elements for some of the circuits.

The obtained results and the drawn conclusions show that the proposed DC converters with ED can be used as charging power supply sources owing to the possibility of working with a wide range of battery parameters.

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