A Fuzzy Logic Application for Go-Kart : a Battery Charger

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Abstract: *While electric and hybrid vehicles are evolving, their batteries had to be replaced and charged as quickly as possible to guarantee their life span. The battery chargers must charge any range of battery. These chargers are mainly based on microcontrollers. The microcontroller checks the batteries state, regulates and stops the battery charge process, displays the charge parameters, recover sulfated batteries and protects them against overheating. Therefore, the regulation of the electrical quantities must be independent from the batteries parameters. In this article, a fuzzy logic based regulator is chosen to regulate the battery charge process of a 12 V-100A electric accumulator. The battery is installed on an electrical go-kart. After modelling the battery and the step down chopper, the current-regulated driver is studied, simulated, and finally experimented with a classical integral corrector, then with a fuzzy logic based corrector.*

Keywords: battery charger, fuzzy logic, robustness, PIC 18F6520.

1. Introduction

While electric and hybrid vehicles are evolving, their batteries had to be replaced and charged as quickly as possible to guarantee their life span. Therefore, the regulation of electrical quantities must be independent from batteries parameters. In this article, we intend to use fuzzy logic for its stability to perturbations and for its easy programming. The battery chargers must be able to charge any range of battery lead acid and to use any cheap microcontroller. This microcontroller must also check the batteries state, regulate the charge, stop charging, display the charge parameters, recover sulfated batteries and protect them against overheating. The figure 1 shows the different steps of the battery charger.

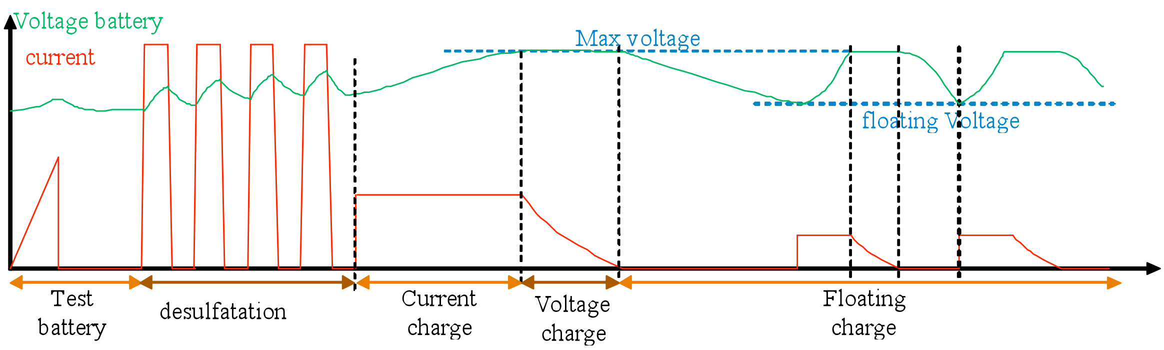

Figure 1. The working steps of charger.

2. Material configuration

From the main voltage 220V AC, a push pull chopper with a power factor corrector provides a 24V–300A voltage. From this voltage, a step-down chopper provides each battery charge process. Charging individually each battery enables to control every threshold voltage per battery. In comparison to a charge of batteries in series, the process threshold voltage can be overdriven because there are asymmetries between the batteries. However, it increases the number of chargers. We use here an accumulator composed of four batteries in series, of spiral lead technology, of the OPTIMA brand. The batteries can provide 900 A as discharge currents and receive 300 A as very quick charge currents. The 4 step-down choppers of 100A are controlled by Pulse With Modulation (PWM) 8 bits to 40 kHz. The microcontroller for regulation is PIC16F6520. The current measurement is carried out with Hall effect sensors from LEM.

3. The battery modelling

The model parameters of an electrochemical converter vary depending on the volume, the electrodes surface, the type of electrodes, the status of charge process, the number of cycles, the temperature and the age. The simplest model is an electromotive force (EMF) noted E_B in series with a resistor noted R_B. But the model of a battery is much more complex with, notably, an important value capacity at these terminals. The charger must work with different types of batteries whose energetic capacity and technology as Ni-MH or Li-Po are also different. Thus, there is no need to consider a complicated model. The choice has been fixed here to an EFM denoted by E_B in series with a resistor denoted by R_B.
The batteries type as Pb, Ni-MH and Li-Po are first charged by a constant current then at a constant voltage and finally either by a holding voltage or disconnected. The batteries voltage must not exceed a critical threshold voltage. So the voltage must be precisely regulated to avoid the battery destruction. The charge current parameter must be modified according to the current energetic capacity.

The next section focuses on the current regulation process then on the regulation of the threshold voltage.

4. The battery current and voltage regulation

4.1. Modeling the battery and the step-down chopper

The average voltage at the bounds of a battery is given by the following equation:

$$U_{B\,moy} = \alpha \cdot U_{ali} - R_L \cdot I_B \qquad (1)$$

where $U_{Ali} = 24$ V and α equals the duty cycle in the range [0, 1] (see on fig. 2).
The resistor R_L of the chopper filter inductance L will not be neglected given that the charge current may reach 100 A in our application. The equation of the battery current is given by the following equation:

$$I_B(p) = \frac{U_{B\,moy} - E_B}{R + L.p} \qquad (2)$$

where p is the Laplace variable and $R = R_B + R_L$

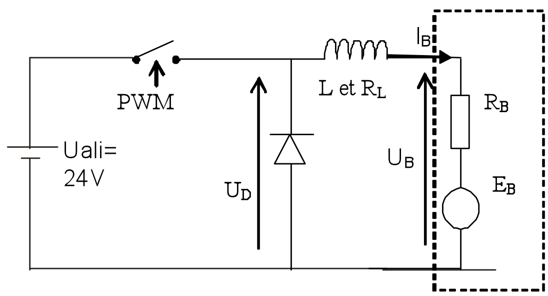

Figure 2: The switch power supply of the battery charger. (Step down converter)

The L/R time constant is very much higher than the chopping period but L/R is very inferior to sampling period of regulator which has been arbitrarily fixed to 20 ms. Therefore, the battery current will have to reach its rate established at each sampling period, so the inductance could be neglected. The model of the current and voltage regulation can be represented by the following diagram on figure 3.

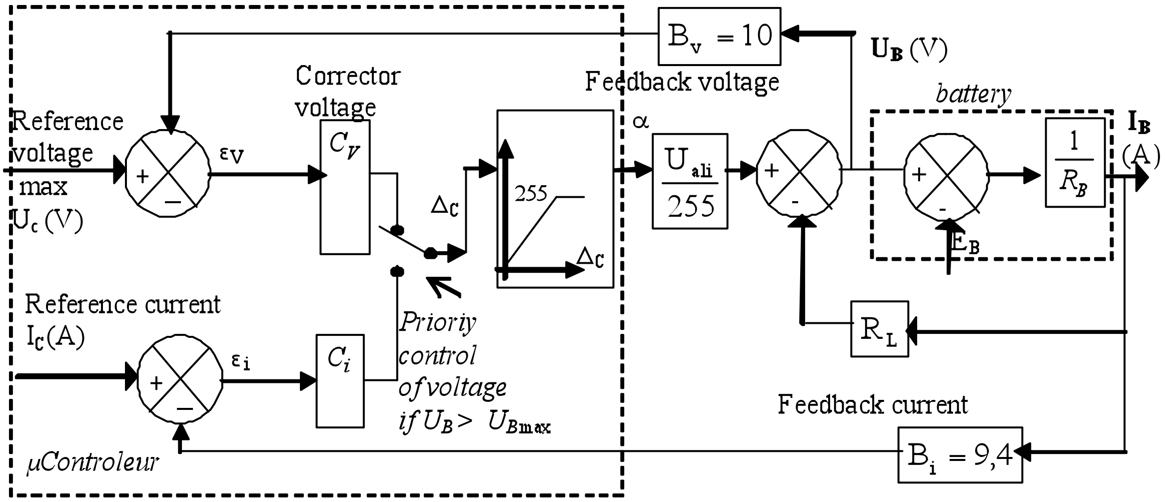

Figure 3: The control scheme regulator of current and voltage

4.2 Current regulation with an integral corrector

The electromotive force of the battery provokes a static error. A pure integral corrector $C_i(p)=(\varepsilon_i(p).k_i)/p$ will cancel the static error without obtaining any overdrive. The first order transfer function of the current is given by:

$$I_B(p) = \left(\frac{I_C}{B_i} - \frac{E_B \cdot p}{A \cdot B_i}\right) \cdot \frac{1}{1 + p \cdot \tau} \qquad (3)$$

With I_c reference current, A= $\frac{k_i \cdot U_{ali}}{255}$, k_i is the integrating factor. The time constant of the loop is defined by:

$$\tau = \frac{R}{A \cdot B_i} \qquad (4)$$

Where $R_{mini}=R_L=10m\Omega$ and B_i = 9,4 is the feedback coefficient.

The time constant depends on R_B. Moreover this classical regulation depends on the current measurement. Given that the low values of the resistors R_B and R_L, a current measurement error can cause large output current variations. A unit minimal shift of the duty cycle Δα will cause a current variation given by the equation:

$$\Delta I_B = \frac{\Delta\alpha \cdot A}{R_L + R_B} = \frac{1 \cdot 24}{255 \cdot (0.01 + 0.02)} = 3 \text{ A} \qquad (5)$$

In order to fix the problem, the current measurement is treated with an analog filter. As some perturbations always exist, this type of regulator is not correct for the system due to the large variation of the duty cycle Δα. A step response integral corrector is thus preferred.

4.3 Current regulation with a unit integral corrector

The step response integral corrector no longer depends on the current measurement but only on the error sign. To prevent the wide output variation, the increment is chosen equal to one step according to the sampling period T_e as shown on figure 4.

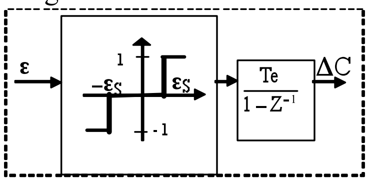

Figure 4: Automatic schematic of the corrector.

The algorithm for the corrector is given by the following statements where ε denotes the error.

if error $\varepsilon > 0$ then $\Delta C(z) = Te/(1-z^{-1})$
if error $\varepsilon < 0$ then $\Delta C(z) = - Te/(1-z^{-1})$
if $|\varepsilon| < \varepsilon_s = 0$ then $\Delta C(z) = 0/(1-z^{-1})$

This type of corrector allows to be fewer dependents of the output measurements, of the variations of E_B and R_B. Nevertheless, the output dynamics are very slow and satisfy the following equations:

$$I_B(n.Te) = (n \cdot Te \cdot A - E_B)/R_B \qquad (7)$$

With E_B=12V, $R_B=20m\Omega$

For a set input of 50A, it is necessary to wait 68 sampling periods for the regulator reaches the current. With a sampling period equals to 20ms, the output current will achieve in 1.36s, the reference but this time is negligible compared to a charge time of one hour.

4.4 The battery current regulation with fuzzy logic

A fuzzy controller is used in order to minimize the influence of the current measurement and to increase the dynamic of current I_B [1]. The structure of the fuzzy regulator is given by the figure 5.

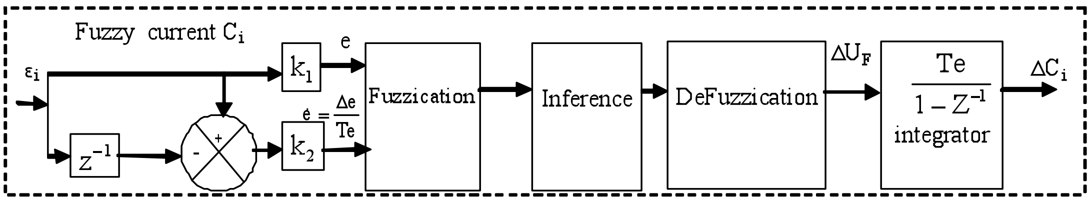

Figure 5: control scheme with fuzzy logic

The principle [3, 7] of the output dynamics by the fuzzy regulator is based on the changing of U_F depending on the point which represents the status of the system in the normalized phase plan (see on fig.6)

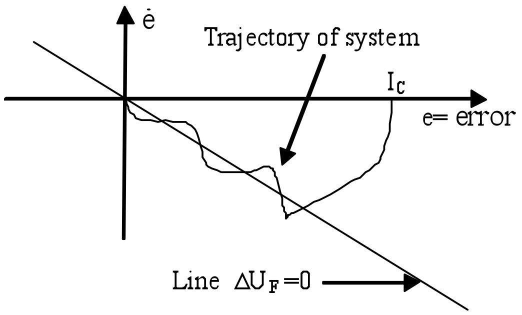

Figure 6: Trajectories in phase plane

Once the point representing the system state matches the wanted dynamics output then ΔU_F is zero [4, 5]. The fuzzy controller with its rules of inference and the membership functions e_n and $\dot{e}_n$ of triangular shape is given on figure 7.

$\dot{e}_n / e_n$	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**
4	0	0.5	1.5	2	3	4	5	5	5
3	-0.5	0	0.5	1.5	2	3	4	5	5
2	-1.5	-0.5	0	0.5	1.5	2	3	4	5
1	-2	-1.5	-0.5	0	0.5	1.5	2	3	4
0	*-3*	*-2*	*-1.5*	*-0.5*	*0*	*0.5*	*1.5*	*2*	*3*
-1	-4	-3	-2	-1.5	-0.5	0	0.5	1.5	2
-2	-5	-4	-3	-2	-1.5	-0.5	0	0.5	1.5
-3	-5	-5	-4	-3	-2	-1.5	-0.5	0	0.5
-4	-5	-5	-5	-4	-3	-2	-1.5	-0.5	0

Figure 7: Inference table of fussy logic regulator

For an easy implementation on a microcontroller that carries on some calculation, the fuzzy controller is based on the table given on figure 6. The command U_F is deducted directly from the table ($k_1.e$, $k_2.\dot{e}$). The line of zero on figure 6 is called the switching line. The trajectory of the controlled system in the phase plan is sliding up and down along this line [2, 6]. Thus, the controlled system is defined par the sliding line equation:

$$S(e, \Delta e) = k_1.e + k_2.Te\ \Delta e = 0 \qquad (8)$$

The first order differential equation (8) gives the following solution:

$$I_B(n.Te) = (I_{B(x\cdot Te)} - I_C)\cdot e^{\frac{-k_1}{k_2\cdot T_e}\cdot(n\cdot Te)} + I_C \qquad (9)$$

The time constant is equal to the slope of the switching line that is D_c ($-k_2.Te/k_1$). The scale factors k_1 and k_2 determine the output dynamics of the fuzzy controller. The scale factor k_1 acts on the accuracy of the error. The accuracy is equal to the set point divided by 4 according to the table given on figure 6. By example, for a step reference of 100 A and a scale factor $k_1=1$, the accuracy of the membership function is equal to 25 A. The accuracy is not enough. It is thus necessary to increase the accuracy to a value which is slightly higher than the current wave caused by the chopper of supply. The scale factor k_1 must be modified depending on the output by the following scheme.

$$\text{if } I_C > |e| > I_c/4 \text{ then } k_1 = 4 / I_C = 0,04 \qquad (10)$$

$$\text{if } I_C > |e| > I_c/4^2 \text{ then } k_1 = 4^2 / I_C = 0,16 \qquad (10)$$

$$\text{if } I_C > |e| > I_c/4^3 \text{ then } k_1 = 4^3 / I_C = 0,64 \qquad (10)$$

where reference current $I_{C\,max}$=100A.

The scale factor changing can be seen in [4] where the author proposes a modification of the scale factor when the position of the system reaches the reference to cancel static error. The next part focuses on the battery voltage control.

4.5 The battery voltage regulation

The resistance of the inductance R_L of the step down converter brings a static error on the regulation voltage. The same problems as the current regulation occur while limiting the voltage at the battery bounds to the threshold voltage. A classical integral corrector allows to cancel the static error. The transfer function is given by

$$U_B(P) = (\frac{U_C}{B_v} - \frac{R_L \cdot I_B \cdot P}{A \cdot B_V}) \cdot \frac{1}{1 + p \cdot \tau} \quad (11)$$

where the time constant equals

$$\tau_V = \frac{1}{A \cdot B_V} \quad (12))$$

As for the current regulation process, a voltage measurement error can bring a large output voltage variation. For example, a unit shift of ΔC provokes the following voltage variation:

$$\Delta U_B = \Delta C \cdot A = \frac{1 \cdot Uali}{255} = 0.1V \quad (13)$$

The voltage measurements are analogically and digitally filtered. For The same reasons seen in the current regulation, we use a fuzzy regulator.
The next part presents the simulations and experimental results with a fuzzy regulator.

5. Implementation of a fuzzy regulator

5. 1. Simulation

The electronic simulator ISIS is used to simulate the microcontroller program, the chopper and the battery. Thus, it includes the Spice models of the MOS transistor, the diode, the inductance filtering, the battery and the sampling period equal to 20ms.
To see the advantage and disadvantages of the two latest regulations presented, we simulate a step response at 50A. After 690ms, the reference will change from 50A to 10A.
These two references allow to see the output dynamics and observed the advantages and disadvantages of the two latest regulations presented.
The choice of scaling factors of fuzzy controller must have a time constant higher than the sampling period. This time constant is chosen arbitrarily (-k2.Te/k1) = 80ms. The scale factor k1 is chosen to satisfy the conditions of equations (10) and the factor k_2.

The two following figures 8,9 show the current and the battery voltage according to time. With the fuzzy controller, the current shows a faster dynamic because of the table or inference Δ C is greater than 1 relative to the corrector of Figure 3. There is no overshoot of the current but there is a current oscillation around the reference 50A in Figure 8 for a minimum period 2.Te because the output corrector of Figure 3 switch. This oscillation is not present for the fuzzy control by changing the scale factors k1. It can also be noticed that the current which reaches its steady state for each sampling period of 20ms.

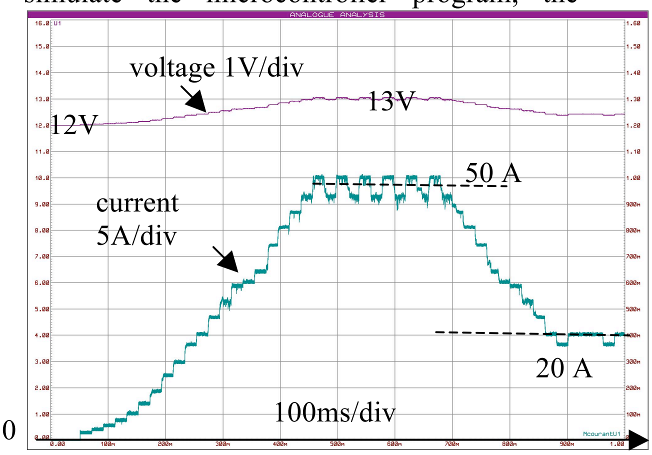

Figure 8 : Simulation of the battery current of the corrector given in the figure 3

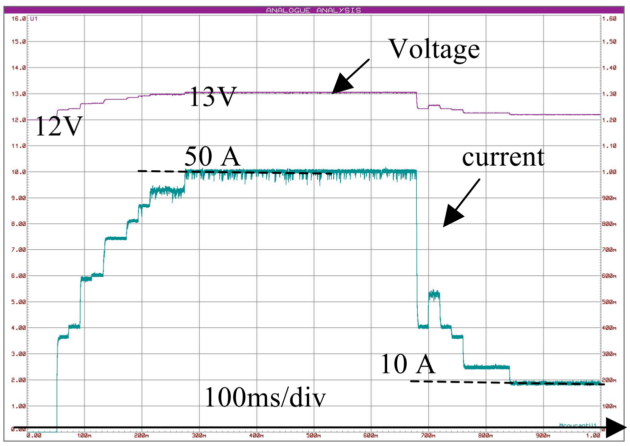

Figure 9 : Simulation of the battery current using a fuzzy corrector

After validating those simulations, the rest of the paper consists in the implementation of the two controllers.

5.2 Experimentation results

The fuzzy regulator installation has been done on the PIC 16F6520 microcontroller which includes 4 PWM outputs to remote the 4 converters DC. A LCD display shows the main information from the charger.
The current is measured from the oscilloscope by the use of a Hall effect sensor and a difference amplifier. The figure 10,11 show that the experimental measurements are closed to the simulation results. The chopper oscillation current is equal to 3 A.
The parameters of the batteries are slowly varying. Depending on the time for loading the battery, 30 minutes for a high unload or a few minutes for a Small unload, a greater sampling period could have been chosen equal to one second for example.

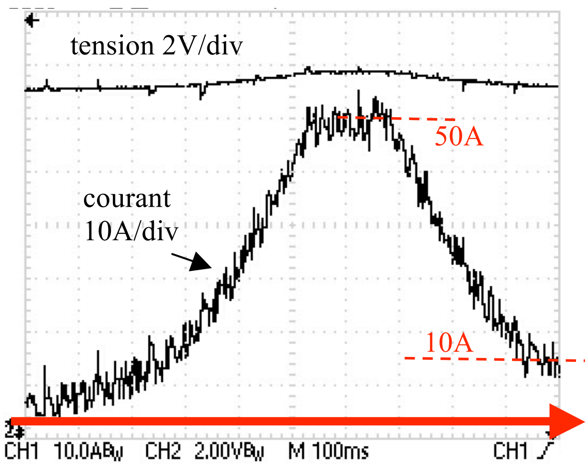

Fig 10: Experimental measurements of the battery current of the corrector given in figure 3

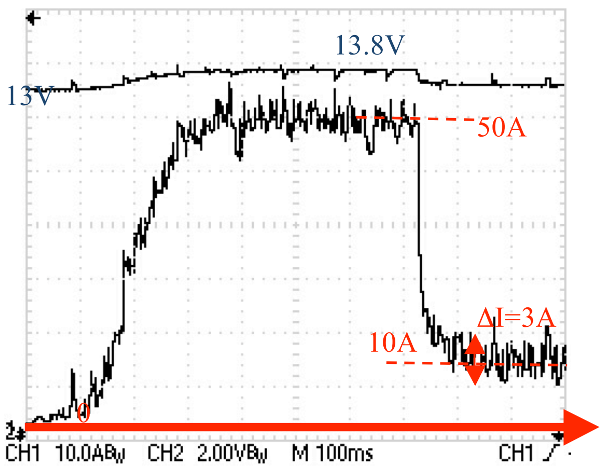

Figure 11 : Experimental measurements of the battery current using a fuzzy corrector

6. Conclusion

The paper shows how a fuzzy controller can be useful to control a battery charger because of the oscillations due to the chopper device. As the regulator requires few computing line codes, it can be used with cheap microcontroller. The regulator offers robustness on large energy capacities of batteries. These advantages allow the regulator to be installed on a wide range of batteries with different technologies. Most of the battery analogic chargers are based on a current range and they do not work with constant chopping frequencies. This article proves that it is possible to control the current directly by the microcontroller. Thanks to the microcontroller, the overflow of maximum current and thread voltage will not occur. Nevertheless each technology needs to define the current and voltage in according to the capacity energy requirements.

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