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Output Feedback Control of Bidirectional DC-DC Power Converter for BEV Charger

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Abstract— **This paper deals with the problem of controlling a bidirectional dc-dc power converter stage for battery electric vehicle (BEV) charger. The power converter operates in two modes: charging mode (buck mode) and discharging mode (boost mode). The control objective is ensuring the sensorless inner battery state variable for the battery voltage regulation. After a nonlinear modelling of the whole system (including the bidirectional dc-dc power converter and the battery), a state feedback controller and an observer are designed. It is shown, using theoretical analysis and simulations that the proposed output feedback controller meets the objective.**

Keywords— **bidirectional dc-dc power converter, non-linear model, state feedback control and observer.**

I. Introduction

Due to demand for decreasing CO_2 emission and improving fuel-efficiency of vehicles, research and development of battery electric vehicles (BEVs) is being revitalized worldwide.

But as the number of BEVs on road increase, they will increase the burden on the electricity grid. But on the other hand EVs can be considered as 'mobile power banks' since they store considerable amount of energy and that can be used to benefit the grid [1].

In contrast, in the near future, the concept of vehicle-to-X (V2X), which transmits electricity from an on board battery to infrastructure, is expected to spread. V2X is a collective term for such as, vehicle to live (V2L), vehicle to home (V2H), and vehicle to grid (V2G) and expresses the power flow from vehicles to others (Fig. 1) [3]. For example, V2L is expected, as an emergency power source, to supply electricity from a vehicle to electric appliances directly. V2H and V2G technologies have started to be put to practical use, with the aim of demand peak-cut control, power distribution at electricity failure, and stabilization of grid power. Various demonstration experiments have been carried out and such technologies are now partly in use [2].

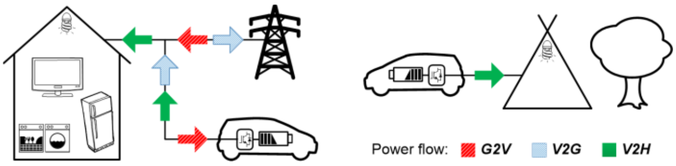

Fig.1. Concepts of the bidirectional battery charger with V2X technologies

An efficient charger system is a key component for electric vehicle. Broadly the EV chargers can be classified into conductive and inductive based on power transfer method. Also they are classified into unidirectional chargers and bi-directional chargers based on power transfer direction [1].

Typically an EV charger consists of two converters: a power factor corrected ac-dc converter which is followed by dc-dc converter for interfacing the battery. But generally such converters are unidirectional in nature so they operate only in G2V charging mode. In order to enable V2X technologies the converter should be bidirectional with sufficient power rating (Fig. 2). In V2G technology the energy stored in vehicle battery is delivered to grid where as in V2H mode the converter supplies the home loads.

In the G2V operation mode, the bidirectional ac-dc converter operates as a rectifier with sinusoidal current absorption, and the reversible dc-dc converter operates in the buck mode. However, in the V2G operation mode, the bidirectional ac-dc converter operates as an inverter with unitary power factor, and the reversible dc-dc converter operates in the boost mode.

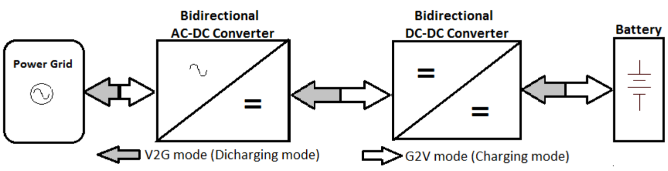

Fig. 2. Typically diagram block of bidirectional battery charger

In this paper, and according to the Fig. 2, the modelling and the control of a bidirectional dc-dc power converter associated with the battery are elaborated. The main contribution of this paper is the battery voltage regulation without sensing the battery inner voltage. To this end, an output feedback controller

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consisting of a state feedback controller and an observer is designed.

The paper is organized as follows: in Section 2, the bidirectional dc-dc power converter is described and modelled; Section 3 is devoted to design a state feedback controller and an observer; in Section 4 the controller performances are illustrated by simulations. A conclusion and a reference list end the paper.

II. PRESENTATION AND MODELLING OF THE SYSTEM

A. System Presentation

The electrical circuit of the studied bidirectional dc-dc power converter associated with the battery is illustrated by Fig. 3, [7]-[10]. It consists of a half bridge converter (two switches K_1,K_2), the filtering inductance L and capacitor C and the battery. The power converter is supplied by a dc-bus voltage.

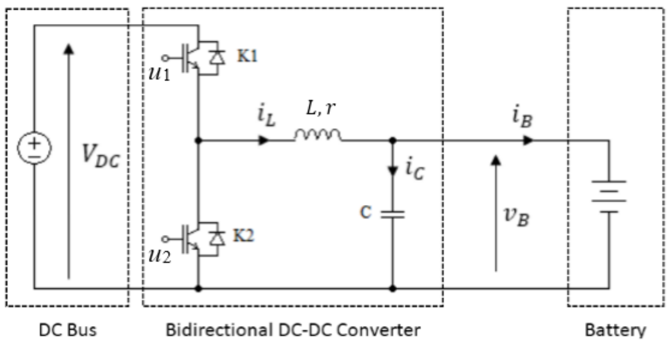

Fig. 3. Electric diagram of the bidirectional dc-dc converter

The dc-dc power converter is used to interface the batteries with the dc-bus. In G2V operation mode this converter operates as a buck converter in order to control the battery current and voltage during the charging stage, respectively. During V2X operation mode, the converter operates as a boost converter to elevate the batteries voltage to an adequate dc-bus voltage aiming to guarantee the proper operation of the bidirectional ac-dc power converter [3].

B. System Modelling

To design a controller, the first step is to elaborate an adequate model describing the system dynamics. This model is obtained considering the two operation modes of the converter (buck mode and boost mode) [11], [12].

The control signals of the switches K_1 and K_2 are denoted, $u_1$and u_2, respectively.

1) Battery Model: In this paper we consider that the battery is modelled by its equivalent electrical circuit illustrated by Fig. 4. The equivalent series resistance (R_B) made up of interconnecting conductors, separators porosity, plate grids, and electrolyte. The equivalent parallel resistance (R_P) represents the impurities in the plates and electrolyte that slowly discharges battery as it is sits unconnected (self-discharge resistance), C_B represents the battery capacitance [5].

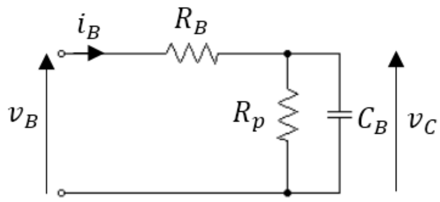

Fig. 4. Electric model of the battery

2) Bidirectional dc-dc power converter modelling: we consider the two operations mode of the converter:

Buck operating mode: In this operating mode, the switch $K_1$is controlled by a PWM signal ($u_1 \epsilon \{0,1\}$)while the switch $K_2$is still open ($u_2 = 0$). The electrical energy then flows from the DC bus to the battery. The dc-dc converter will operate in the buck mode, while the overall system (charger-battery) will operate in G2V mode. In this situation, the equivalent electrical diagram of the converter is shown in Fig. 5.

From inspection of the circuit, shown in Fig. 5, and taking into account that u_1 can take the binary values 1 or 0, the following switching model can be obtained

$$\begin{cases} L\frac{di_L}{dt} = -r\, i_L - v_B + u_1 V_{DC} \\ C\frac{dv_B}{dt} = \, i_L - \frac{1}{R_B}v_B + \frac{1}{R_B}v_C \\ C_B\frac{dv_C}{dt} = \frac{1}{R_B}v_B - (\frac{1}{R_B} + \frac{1}{R_p})v_C \end{cases} \tag{1}$$

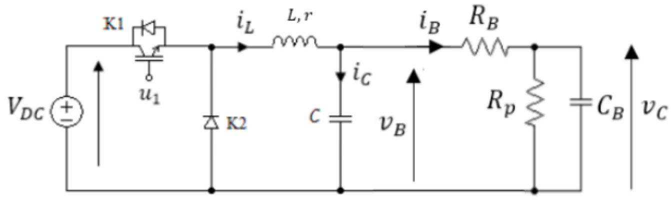

Fig. 5. Electric diagram in buck operating mode

Boost operating mode*:* In this operating mode, only the switch $K_2$is controlled by a PWM signal ($u_2 \epsilon \{0,1\}$)while the switch K_1 is still open ($u_1 = 0$). The electrical energy then flows from the battery to the DC bus. The dc-dc power converter will operate in boost mode, while the overall system (charger-battery) will operate in V2G mode. In this situation, the converter is equivalent to the electrical diagram illustrated by Fig. 6.

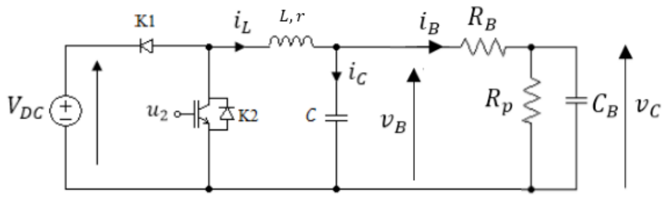

Fig. 6. Electric diagram in boost operating mode

Also, from inspection of the circuit, shown in Fig. 6, and taking into account that μ_2 can take the binary values 1 or 0, the following switching model can be obtained

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$$\begin{cases} L\frac{di_L}{dt} = -r\, i_L - v_B + (1-u_2)V_{DC} \\ C\frac{dv_B}{dt} = i_L - \frac{1}{R_B}v_B + \frac{1}{R_B}v_C \\ C_B\frac{dv_C}{dt} = \frac{1}{R_B}v_B - (\frac{1}{R_B}+\frac{1}{R_p})v_C \end{cases} \quad (2)$$

Model in bidirectional operating mode: On the basis of the previous two partial models ((1) and (2)), the aim now is to obtain a global model of the system useful for control design purpose. From the inspection of (1) and (2), one can ready obtain the following bidirectional dc-dc power converter model

$$\begin{cases} L\frac{di_L}{dt} = -r\, i_L - v_B + \alpha V_{DC} \\ C\frac{dv_B}{dt} = i_L - \frac{1}{R_B}v_B + \frac{1}{R_B}v_C \\ C_B\frac{dv_C}{dt} = \frac{1}{R_B}v_B - (\frac{1}{R_B}+\frac{1}{R_p})v_C \end{cases} \quad (3)$$

where

$$\alpha = (Su_1 + (1-S)(1-u_2)) \quad (4)$$

The parameter S is introduced in order to take into account the two operating modes of the converter

- $S = 1 \Rightarrow$ buck operating mode;
- $S = 0 \Rightarrow$ boost operating mode.

Equation (4) clearly shows the nonlinear behaviour of the controlled system.
For control design purpose, it is more convenient to consider the following averaged model, obtained by averaging the model (7) over one switching period [4]

$$\begin{cases} \dot{x_1} = -\frac{r}{L}x_1 - \frac{1}{L}x_2 + \mu\frac{V_{DC}}{L} \\ \dot{x_2} = \frac{1}{C}x_1 - \frac{1}{R_BC}x_2 + \frac{1}{R_BC}x_3 \\ \dot{x_3} = \frac{1}{R_BC_B}x_2 - (\frac{1}{R_BC_B}+\frac{1}{R_pC_B})x_3 \end{cases} \quad (5)$$

Where x_1, x_2 and x_3 denote the average inductor current $<i_L>$, the average capacitor voltage $<v_B>$ and the average capacitor voltage $<v_C>$, respectively. The control input for the model (5) is the function μ (average value of α), called duty ratio function. According to the model (5) the following state space representation of the whole system is obtained

$$\begin{cases} \dot{x}(t) = A\,x(t) + B\,\mu(t) \\ y(t) = C\,x(t) \end{cases} \quad (6)$$

where

$$A = \begin{bmatrix} -\frac{r}{L} & -\frac{1}{L} & 0 \\ \frac{1}{C} & -\frac{1}{R_BC} & \frac{1}{R_BC} \\ 0 & \frac{1}{R_BC_B} & -(\frac{1}{R_BC_B}+\frac{1}{R_pC_B}) \end{bmatrix} \quad (7)$$

$$B = \begin{bmatrix} \frac{V_{DC}}{L} & 0 & 0 \end{bmatrix}^T \quad (8)$$

$$C = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \quad (9)$$

In this paper, it should be noticed that the control objective is to ensure a tight battery voltage regulation, the state variable x_2 is then considered as the output of the system $(y(t) = x_2)$.

III. Output feedback controller design

Once the system is modelled, the design of the controller will be done in two steps. The first step is devoted to the state feedback gain determination and the second one is devoted to the observer design.

A. State feedback Design

In this paper we consider an optimal control law that minimizing the following criterion

$$J = \int_0^\infty x^TQx\,dt + \int_0^\infty \mu^TR\mu\,dt \quad (10)$$

Where Q is a real symmetric matrix and positive semi-definite, R is a positive definite matrix.
The proposed control lawμ is as follows

$$\mu(t) = -Kx(t) + Gy_{ref} \quad (11)$$

Where K and G represent the state-feedback gain and the reference gain, respectively.
According to the Linear Quadratic (LQ) control technique [6] the gain K is determined as follows

$$K = R^{-1}B^TP \quad (12)$$

Where P is the solution of the algebraic Riccati equation

$$A^TP + PA - PBR^{-1}B^TP + Q = 0 \quad (13)$$

In order to maintain the steady state error of the closed loop system equal to zero, the gain G is determined so that the static gain of the closed loop transfer function is set to unity. To this end this gain is obtained as follows

$$G = [C(BK-A)^{-1}B]^{-1} \quad (14)$$

B. Observer design

The proposed control law (11) requires the measurement of the battery inner voltage v_C which is not accessible for measurement. To overcome this issue an observer is needed in order to estimate all the state variables. The use of the estimator is also motivated by the global cost and reliability considerations. Indeed, the fewer the number of sensors, the lower the global cost.
In this paper, the following Luenberger observer is proposed

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$$\begin{cases} \dot{\hat{x}}(t) = A\,\hat{x}(t) + B\,u(t) + L(y - \hat{y}) \\ \hat{y}(t) = C\,\hat{x}(t) \end{cases} \quad (15)$$

Where L is the observer gain determined so that the matrix $(A - LC)$ is stable (the real parts of the eigenvalues are negatives).

IV. Simulations and Results

The controlled system, illustrated by Fig. 3, is simulated using Matlab/Simulink. It is worth noting that the system is modelled by its instantaneous model ((3)-(4)) while the averaged model (6) is only used for the controller and observer design. The system parameters are listed in Table I. The simulation bench is described by Fig. 7.

TABLE I :
SYSTEM PARAMETERS

Parameter	Value
Switching frequency F_s	$20KHz$
DC bus voltage V_{DC}	*400V*
ESR of inductance r	$0{,}1\Omega$
Filtering inductance L	*1,5mH*
Filtering capacitor C	$700\mu F$
Battery Equivalent Parallel Resistance R_p	$1K\Omega$
Battery Equivalent Serial Resistance R_B	$0{,}06\Omega$
Battery capacitance C_B	*500F*

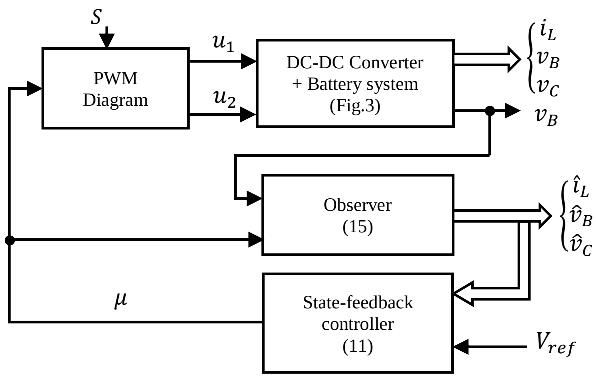

Fig. 7. Simulation bench of the controlled system

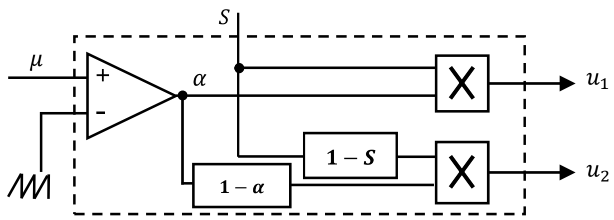

Fig. 8. PWM Diagram

To illustrate the controller performances, one should check the controllability and the observability of the system. In our case this is done by using the Matlab commands *ctrb* and *obsv* which show that the system is as well controllable and observable.
The optimal gain of the proposed controller is also determined using the Matlab command lqr. The matrices R and Q in the criterion (10) are simply chosen as follows $R = 1, Q = C^T C$. With this choice we guarantee the equal importance on the control and the state variable. If the choice $Q = C^T C$ leads to undesirable performances, the controller may be tuned by changing the nonzero element in the Q matrix.
According to the above comments, the gain K vector is given the following value which is convenient

$$K = [0.0436 \quad 0.2685 \quad 0.7299] \quad (16)$$

The gain reference G in (10) is then computed, according to (14), as follows

$$G = 1.0000 \quad (17)$$

Now, we will compute the gain observer L. In practice, one can seek that the observer may converge rapidly than the closed-loop system. A common guideline is to make the observer poles 4-10 times faster than the slowest controller pole. Doing so, and using the fact that $(A - LC)$ must be stable, the vector L is obtained is follows

$$L = [\,3.98\text{x}10^7 \quad 3.8938\text{x}10^5 \quad 1.0806\text{x}10^4]^T \quad (18)$$

The closed-loop system described by the system model (3), the controller (11) and the observer (15) is implemented using Matlab/Simulink software. A simulation bench is illustrated by Fig. 7. According to (4), the PWM diagram is given by Fig. 8. The performances of the closed-loop system are illustrated by Fig. 9 to Fig. 13. Fig. 9 shows the state variables and their estimates during G2V operating mode. As one can be seen, although the initials conditions are different, the estimates converge rapidly to their true variables. It is worth noting that the variables are just plotted in the transitory phase to clearly show the convergence rate. Fig. 10 illustrates that the output voltage v_B perfectly tracks its reference signal $V_{ref} = 200V$. Fig. 11 shows the battery voltage v_B and the battery inner voltage v_C while Fig. 12 illustrates the battery current i_B and the inductor current i_L. Finally, Fig. 13 shows the duty ratio μ during G2V operating mode. As one can be seen, the duty ratio μ is around 0.5.

V. Conclusion

Along this paper was presented a bidirectional dc-dc power converter aiming its integration in bidirectional battery charger with V2X technology in BEVs application. With this characteristic, the BEVs will be able to deliver back a part of the stored energy in the batteries to the power grid, aiming to contribute to mitigate power quality problems.
The studied system consists of a half bridge followed by an LC filter and a battery. The control objective is to enforce the battery voltage to track its desired value without sensing the battery inner voltage. After modelling of the whole system (bidirectional converter-battery), an output feedback controller is designed. It consists of a state feedback controller and an observer. It is shown, using theoretical results and simulation,

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that the proposed state feedback controller achieves the control objective. As future work, the current of the battery will be controlled during the charging mode in order to avoid the over-current in start-up.

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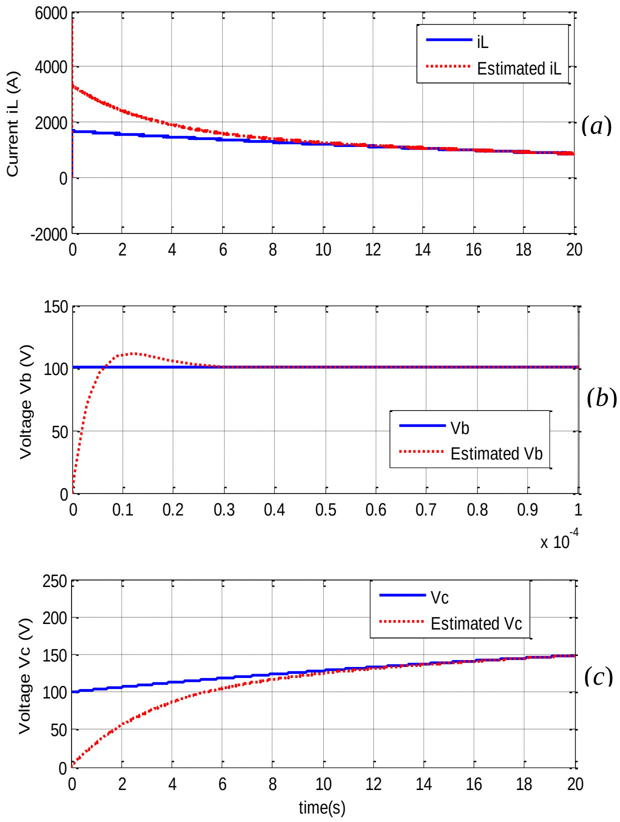

Fig. 9. States variables and their estimates during G2V operating mode

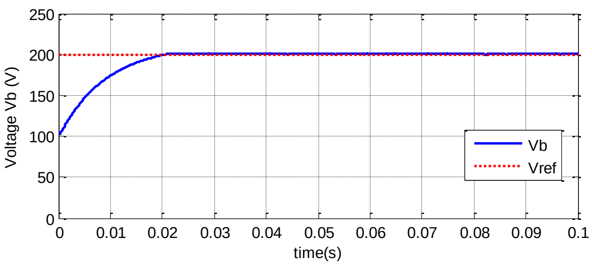

Fig. 10. Battery voltage V_B during G2V operating mode

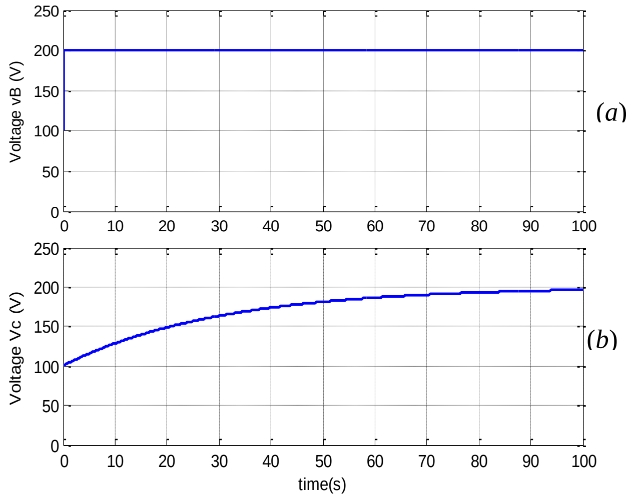

Fig. 11. Battery voltage V_B and inner voltage V_C during G2V operating mode

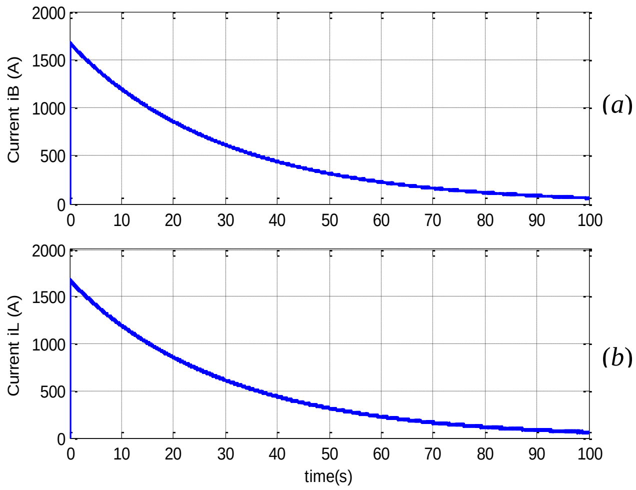

Fig. 12. Battery Current i_B and Current i_L during G2V operating mode

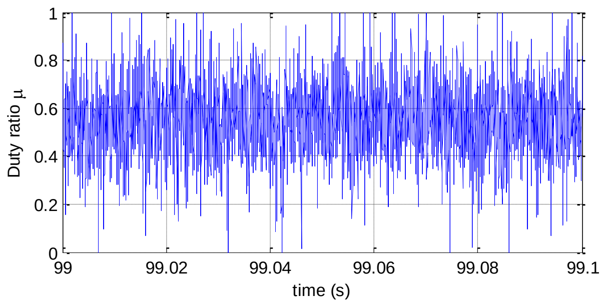

Fig. 13. Duty ratio μ during G2V operating mode

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