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SUBSYSTEM OF POSITIONING THE ACTUATOR FOR AN ELECTRONIC DIESEL CONTROL SYSTEM

Key words: diesel, fuel delivery system, high pressure fuel pump, electronic control, actuator, microcontroller, PID controller.

Abstract: The authors proposed the concept of the synthesis of the algorithm for the electronic diesel controller (EDC), based on the analogy with the operation of a mechanical spring-lever governor of direct action. The system of automatic positioning using HEINZMANN StG 6-02V actuator is developed and practically implemented. A preliminary tuning of the electronic PID controller was performed, which ensured the operation of the actuator with a-periodic transients at a high speed. The present work is a part of the project on the creation of an electronically controlled fuel delivery system for the transport diesel.

Koncepcja sterowania nastawnika elektronicznego układu sterowania silnika o zapłonie samoczynnym

Słowa kluczowe: silnik o zapłonie samoczynnym, układ zasilania, pompa wtryskowa, elektronicznie sterowany nastawnik, mikrokontroler, regulator PID.

Streszczenie: Autorzy zaproponowali koncepcję algorytmu do elektronicznego sterownika silnika o zapłonie samoczynnym, bazując na analogii do działania mechanicznego regulatora dźwigni sprężynowej. Zaprojektowano i wykonano system automatycznego pozycjonowania dźwigni pompy wtryskowej oparty na nastawniku HEINZMANN StG6-02V. Przeprowadzono wstępną regulację elektronicznego regulatora PID, który zapewnił powtarzalną pracę nastawnika z wysoką prędkością. Przedstawiona praca jest częścią projektu stworzenia elektronicznie sterowanego układu zasilania paliwem silnika o zapłonie samoczynnym do użytku drogowego.

Introduction

It is known that many types of diesel engines exploited in the world use fuel delivery systems with mechanical controllers (governors) of the crankshaft rotation speed [1]. A diesel equipped with such a system has a number of disadvantages, e.g., non-compliance with the current environmental pollution standards, pure fuel efficiency, the lack of fuel supply correction depending on the thermal state of the engine and the fuel properties, the lack of torque and smoke emissions during acceleration, etc. The mentioned disadvantages can be partially eliminated through the modernization of the commercial fuel delivery systems by the development of electronic control for fuel delivery processes.

The application of electronics in engine's automatic control systems can significantly improve the fuel economy and emissions characteristics of diesel engines through better matching between fuel and air delivery systems, ensuring engine's operation at optimal modes, and adjusting fuel delivery characteristics depending on ambient conditions and fuel properties [2].

It should be mentioned that the cost of electronic control systems used for the management of diesel engines is high, and their maintenance and repair requires the availability of expensive and complex equipment and, accordingly, highly skilled personnel. In addition, the manufacturers of EDC systems encrypt the software algorithm used for the fuel delivery system management, which makes it impossible to adjust its operation, for example, during diesel's modernization. On the basis of the above, it will be relevant to develop an EDC system for the modernization of widely used fuel pumps with mechanical actuators. The authors of the present article created a working group involved in the mentioned problem-solving.

It should be noted that the creation of such systems of automatic control requires highly qualified specialists in the fields of the fundamental theory of internal combustion engines (ICE), the theory of automatic control, microelectronics, algorithmization, and low-level programming of controllers, etc.

The EDC (Electronic Diesel Control) system is subdivided into three areas "Sensors and desired-value generators," "Control unit," and "Actuators" [3]. A functional feature of the application of electronics in internal combustion engines, in particular, for their automatic control, is a necessity for the proportional transformation of the electrical signals of the electronic control unit (ECU) into the mechanical processes of moving the corresponding elements [4]. For the implementation of such a transformation of information, so-called actuators are used. Electric machines (step or precision electric motors) and electromagnetic or solenoid valves are the most widespread actuators used in ICE [5].

1. The state of current research

It could be stated that commercial production of the fuel delivery systems with electronic control is the prerogative of several leading and world-famous firms such as BOSCH [6], HEINZMANN [7], DELPHI [8], Motorpal [9], etc. It is natural that these manufacturers do not share any information about the components, structure, algorithms, and programs on which their equipment operates. The same approach is taken by small private companies involved in the retrofitting of traditional fuel supply systems with the delivering electronic control solutions to manage it. That is why there are no open publications on this issue.

The authors of the present article have already had a positive experience with the application of a linear step electric motor as an actuator for an electronic control of a fuel delivery system used in the experimental diesel engine that was described in the source [11]. The executive mechanism was proved to be quite reliable and simple in particular algorithm implementation for a fuel delivery system control. However, it was established, during the experiments, that the utilization of linear actuator based on the stepper motor has a number of disadvantages. Among them are non-compact design, insufficient execution speed, and a complicated emergency protection system (if the signal is missed, the actuator «freezes» in the current position).

Therefore, at the present stage of research, the question of choosing the most suitable type of the actuating mechanism for the retrofitting of the hydro-
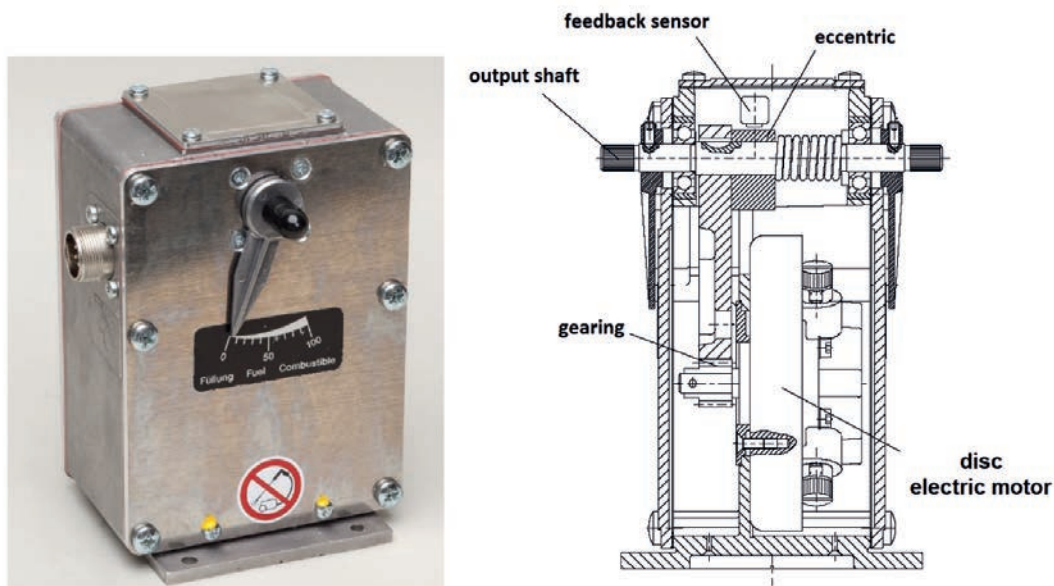

Fig. 1. Actuator *StG 6-02V* [7]

-mechanical system used to control the fuel delivery process is considered. The actuator would implement the software algorithm that was developed at the previous stage of the research [11].

For example, the BOSCH Company's actuators use electromagnets controlled by a Pulse Width Modulation (PWM) signal for positioning and distribution of the rail of inline and high-pressure fuel pumps [10]. The design of such actuators is reliable and common for mass and serial production.

HEINZMANN is another well-known manufacturer of actuators used in a different industry segment, including rotor actuators consisting of brushless electric motors, gears, and built-in position feedback sensor [7]. All actuators of this company are equipped with an electric drive and have the ability to connect control devices that make it easy to install them in an internal combustion engine of any type. At the same time, the choice of the appropriate actuator depends on the effort required to put into operation or maintain in a certain position the element responsible for fuel delivery (fuel rack of the high-pressure fuel pump). As an example, a HEINZMANN actuator, model StG 6-02V, could be considered as the element of engine's electronic control system (Fig. 1). The actuator's design is based on a DC disc motor driven by a PWM signal. It has a toothed gearbox and a non-contact feedback sensor. This actuator provides an output torque of 6 N·m and a range of the angle of the rotation of the output shaft of 36°, and it can be used in the electronic control systems of diesel and gas engines of average power, as well as in the management of steam and gas turbines [7].

It should be noted that the actuator shown in Fig.1 has no some of the disadvantages that the previously described stepper motors have. The advantages are as follows: (1) the presence of a reverse spring that will immediately put the output shaft into a "zero" position when the control signal disappears; and, (2) a high-speed response (response time is 75 ms) that allows it to be used to control high-speed internal combustion engines.

Taking into account all advantages related to *StG 6-02V* actuator, this unit was chosen as a physical object of the present research.

2. Purpose of the current research

There is a number of theoretical and experimental works on the retrofitting of automatic speed control systems for a diesel engine on the basis of electrical actuators from HEINZMANN [7]. The positive scientific results are shown in works [12, 13]. A distinguishing feature of the mentioned research works is that they were conducted using the original ECU of types HELENOS, PANDAROS, and others. Unfortunately, the algorithms and codes used in the ECU are closed as commercial information of the producer and cannot

be cloned or modified. Since the work of the authors is aimed at developing its own electronic system used for the fuel delivery control, the synthesis of the subsystem responsible for actuator positioning is the key task.

The purpose of this article is to describe the development of an electronic system used for actuator's positioning in the drive of the high-pressure fuel pump (HPFP) rack of the diesel engine. The electronic system is created on the basis of a precision electric motor driven by current and includes hardware, and algorithmic and programmatic components.

3. The scheme of the control system and the algorithm implemented in the actuator

The new approach to the synthesis of an electronic controller algorithm is proposed for controlling the rack of a high-pressure fuel pump. The approach is based on the analogy with the operation of a mechanical spring-lever direct-acting governor. Such governors are used in a lot of diesel engines that operate worldwide and provide acceptable (but not optimal) operational regulatory characteristics. It is generally believed that they are sufficiently reliable aggregates.

The new hypothesis from the authors is as follows: The displacement of the regulating element (the magnitude of the regulatory influence) Hp_0 positively depends on the position of the fuel supply control unit X, and negatively depends on the current crankshaft rotation speed (angular velocity of the crankshaft) n, that can be described by the following formula:

$$Hp_0 = A_1 + A \cdot X - B \cdot n \qquad (1)$$

where A_1, A and B – constant (or variable) coefficients.

The application of the proposed algorithm creates a direct analogy to the kinematics of a mechanical all-speed governor with variable spring tightening, illustrated by the diagram in Fig. 2. As can be seen in Fig. 2, the value of ΔX characterizes the movement of the control lever 7 (point E), the term $B \cdot \Delta n$ is the position of the clutch of the governor 3, on which the centrifugal force of the loads (point B) acts and thus the value of ΔHp is a unique position of the rack of HPFP 6 (point D).

The coefficients A_1, A, and B in Formula (1) characterize the ratio of the arms AD, AC, and AB of the regulator's lever 5. The magnitude of these coefficients is determined based on the given degree of irregularity, the coefficient of adaptability, and the maximum allowed crankshaft rotation speed. Therefore, the selection of these coefficients can provide the desired shape (incline) of regulatory characteristics (or the universal characteristic of the diesel). An example of

the synthesis of such characteristics that utilize defined values of the mentioned above coefficients is shown in Fig. 3. The regulatory characteristics were developed for the BOSCH-type, in-line high-pressure fuel delivery pump that is used for the fuel supply of 4 cylinder diesel engines.
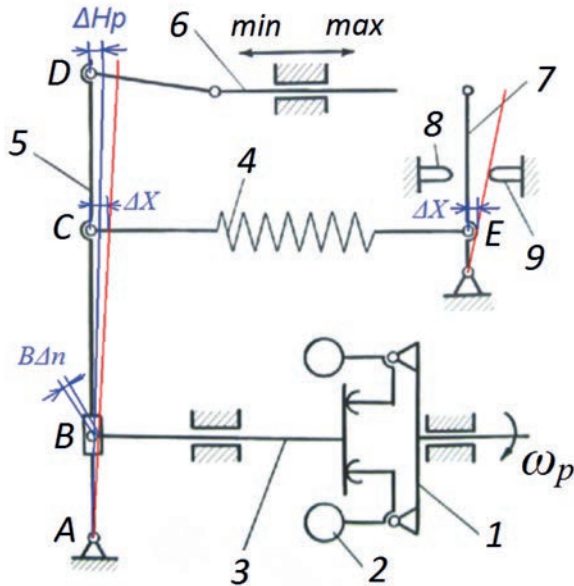

Fig. 2. Principal scheme of the mechanical all-speed governor: 1 – sensitive element; 2 – loads of the sensitive element; 3 – clutch of the governor; 4 – spring of the governor; 5 – the lever of the governor; 6 – rack of HPFP; 7 – lever control; 8 – limiter ω_{min}; 9 – limiter ω_{max}
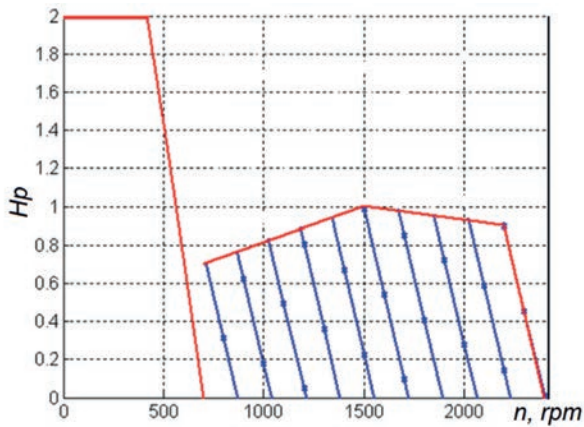

Fig. 3. Regulatory characteristics of the high-pressure fuel pump provided by the proposed algorithm

Thus, without introducing any structural changes in the fuel delivery system or in the governor, it is possible to match the characteristics of the engine to obtain the desired performance characteristics of the vehicle. It is important to mention that the same approach (based on the Formula (1)) can also be used to synthesize the

algorithm of an electronic regulator for a Common Rail fuel delivery system with electro-hydraulic injection.

The proposed functional diagram of the electronic system used for automatic control of the engine speed (ACES) is presented in Fig. 4. The subsystem of the actuator›s management is highlighted in the functional diagram. As can be seen in the figure, the main external and internal influences of ACES are as follows: X – the current position of the engine control element, n – the current crankshaft rotation speed, Hp – the position of the fuel delivery control element (the rack of HPFP), and f – the relative magnitude of the PWM signal stuffing. The governor of the actuator is part of the engine control algorithm stored in ECU.

The algorithm of the operation of the subsystem of the actuator's governor is given below.
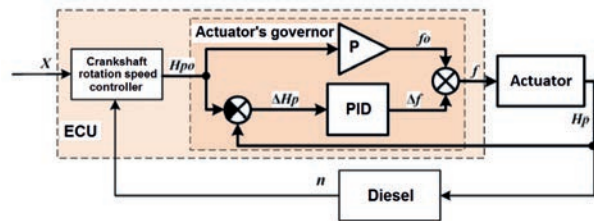

Fig. 4. Functional diagram of the ACES electronic system

Taking into account the presence of a reverse positional relation, according to the current valid position of the HPFP rack, the value of the "discrepancy" could be calculated as follows:

$$\Delta Hp = Hp - Hp_0 \qquad (2)$$

The developed algorithm for controlling the actuator is based on the parallel work of Positional (P) and Proportional Isodromic Derivative (PID) controllers as shown in Fig.4. In this case, the P-controller is, in essence, a non-inertial amplifier and determines the required level of PWM signal stuffing in order to achieve a given equilibrium position of the rack Hp_0 and this is equation has a fairly simple form:

$$f_0 = K \cdot Hp_0 \qquad (3)$$

Working in parallel with the P-controller, the PID-controller, on the basis of the magnitude of the discrepancy determined by Formula (2), ensures the rapid achievement of a given position Hp_0 by means of the program implementation of the following expression:

$$\Delta f = K_D \cdot \Delta^2 Hp + K_P \cdot \Delta Hp + K_I \cdot S \qquad (4)$$

Thus, the current stuffing of the PWM signal submitted to the actuator's executive mechanism has the following value:

$$f = f_0 + \Delta f \qquad (5)$$

After analysing Formulas (3) and (4), it is not difficult to notice that the first formula describes static characteristics, and the second determines the dynamic properties of the whole system.

The differential component in expression (4) is defined as follows:

$$\Delta^2 Hp = \Delta Hp(t) - \Delta Hp(t - T) \qquad (6)$$

where: $T = 120/n$ the timing period, which depends on the current crankshaft rotation speed n and, in fact, determines the time constants of integration and differentiation.

And the term of the isodromic component S from the same expression (4) is calculated by means of the recurrence formula:

$$S(t + T) = k_I \cdot S(t) + \Delta Hp(t) \qquad (7)$$

In formulas (6) and (7), t is the current instant of time, and k_t is the isodromic coefficient.

The block diagram of the hardware implementation of the developed electronic governor, on the basis of the actuator *StG 6-02V,* is shown in Fig. 5.

The main components included in the scheme, in addition to the actuator itself, are as follows:

– Atmel *SAM3X8E ARM Cortex-M3* microcontroller with a clock frequency of 84 MHz, 96K RAM and 512K programmable memory, with an output frequency of the 12-bit PWM signal of 488.28 Hz;
– *Weir LAMBDA HSS100* power supply unit of 330 W; and,
– An integral bridge driver of electric motor *BTS7960V* with a limiting output current of 43 A, and the support of PWM frequency up to 25 kHz.

In order to record transient modes, there is an SD *Card SPI* connection module introduced in the circuit.

It is well known that, in order to ensure the quality of the PID-control of the system, it is necessary to solve the difficult task of selecting and optimizing the values of
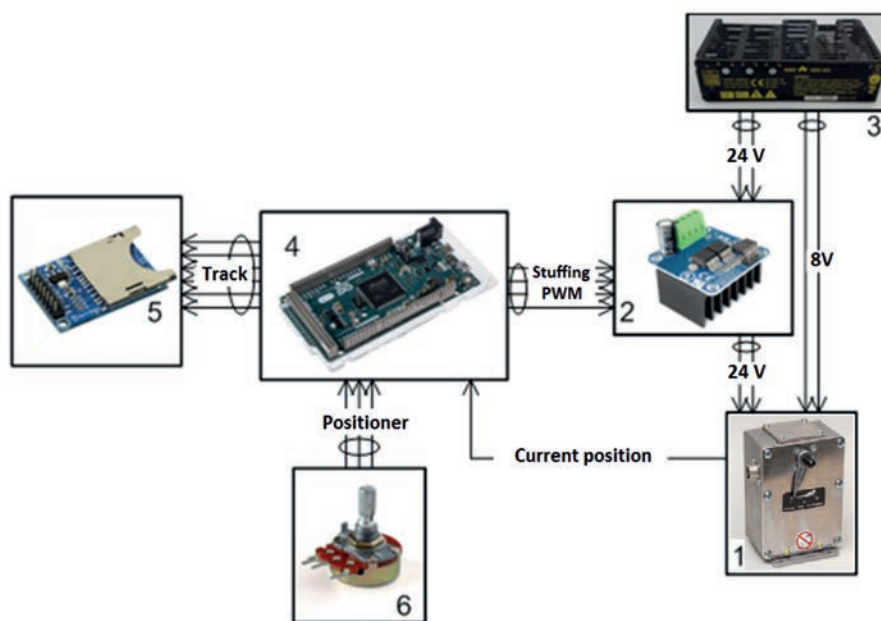

Fig. 5. **Block diagram of the governor with actuator: 1 – actuator; 2 – electric motor driver; 3 – power supply unit; 4 – microcontroller; 5 – the module for connecting a memory card; 6 – potentiometer**

the coefficients included in the equation of the governor. In the current solution, these quantities are K_D, K_p, K_1 in Formula (4) and K in the Formula (3). There are two possible ways to solve it. The first solution is the creation of mathematical models that describe the governor and the object of regulation in the form of a system of differential equations, with subsequent calculations based on special methods of the theory of automatic control [14]. The second way is to experimentally select

the values of the coefficients ("manual tuning"), which is based on some empirical rules and techniques (e.g., the Siegler-Nichols method, CHR, etc. [15]).

At the previous stage, the problem of choosing essential coefficients was solved by the author using the second method, taking into account ensuring the robustness of the system at such a variable value of the timing period T, which corresponds to the possible range of crankshaft rotation speeds n.

The transmission coefficient (amplification coefficient) K in Formula (3) has a simple physical meaning: This is the required value of stuffing the PWM signal by the unit of the relative positioning of the output shaft for a given actuator. Its value was detected through analysis of the angle of the *StG 6-02V* actuator static characteristic inclination in the form of the *Hp(f)* function.

As a result of a series of special laboratory experiments, the optimal values of the PID controller coefficients were found on the experimental setup (Fig. 5). Their relative weight values are $K_D \approx 20\%$, $K_p \approx 50\%$, $K_1 \approx 30\%$. Such a configuration ensured the convergence of transient processes with low oscillation in the whole range of the timing period and can be considered as satisfactory at the present stage of the research. As an example in Fig. 6 and Fig. 7, there are records of the system track. As can be seen from the charts, the developed system provides astatic positioning of the output shaft of the actuator *Hp(t)* for a given position $HP_0(t)$.
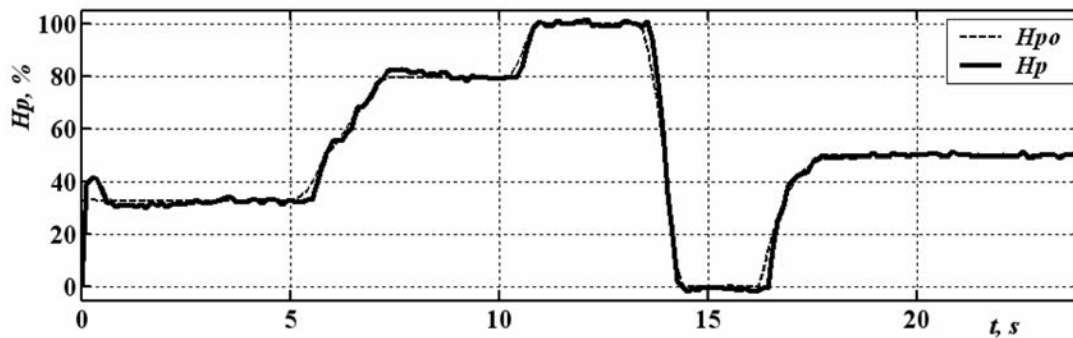

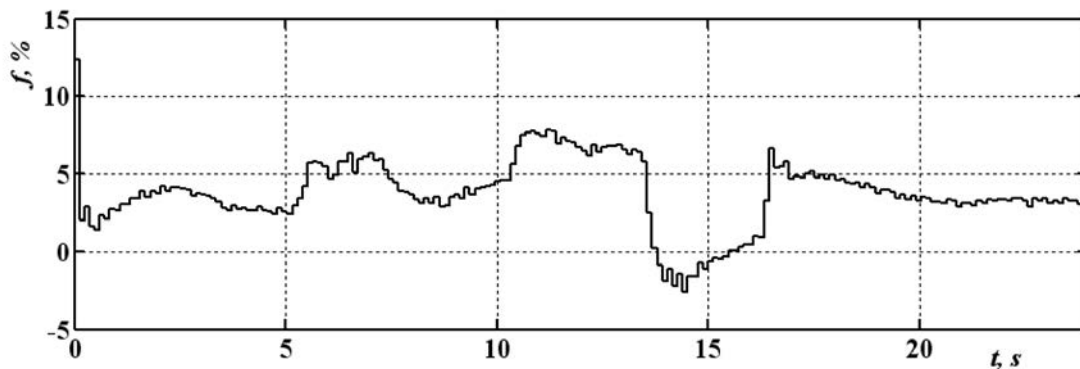**Fig. 6. Control element displacement (output signal)**

Fig. 7. Changing the value of the PWM signal stuffing (input signal)

Conclusions

According to the results of the present work, the following conclusions could be reached:
1. The concept of the synthesis of the algorithm of the electronic governor in a diesel engine, based on the analogy with the work of the mechanical spring-lever direct-acting regulator, is proposed and implemented.
2. A functional scheme and an experimental sample of the electronic governor used for the control of the crankshaft rotation speed of a diesel engine have been developed.
3. The system of automatic positioning of the HEINZMANN *StG 6-02V* actuator has been developed and practically implemented. Actuator design is based on a precision electric motor driven by current.
4. The pre-setting of the electronic PID-controller was made. They provided the operation of the actuator with astatic characteristics at high response speed.

This work is part of the creation of an electronic system used for the management of the diesel's fuel delivery system. The next stage of the work assumes motorless bench tests of the high-pressure fuel pump with the integrated governor in order to obtain the required static regulatory characteristics of the unit.

Acknowledgements

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