Threat Analysis of Vehicle Engine Electronic Control Unit in Severe Electromagnetic Pulse Environment and Research on Protection

Xie Ma[1,2]
[1]*China Electronics Technology Cyber Security Co., Ltd*
[2]*Chengdu Xinxin Shenfeng Electronics S&T Co., Ltd*
Chengdu, China
18081045600@163.com

Haoyue Zheng
China Electronics Technology Cyber Security Co., Ltd
Chengdu, China
z_haoyue@163.com

Yu He
China Electronics Technology Cyber Security Co., Ltd
Chengdu, China
my_email_3@163.com

Dzmitry Tsyanenka
EMC R&D Laboratory
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
emc@bsuir.by

Vladimir Mordachev
EMC R&D Laboratory
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
mordachev@bsuir.by

Eugene Sinkevich
EMC R&D Laboratory
Belarusian State University of Informatics and Radioelectronics
Minsk, Belarus
sinkevich@bsuir.by

***Abstract*—The severe electromagnetic pulses generated by nuclear blast or high power microwave cause serious electromagnetic threats to the vehicle Electronic Control Unit (ECU) through the way of field-wire coupling. This kind of threat affects the performance of mobility, and also the vehicle safety. This paper focuses on a typical multi-use vehicle, the effect mechanism of the ECU in the severe electromagnetic environment is analyzed, the broadband Electro-Magnetic Pulse (EMP) radiated test for the vehicle is carried out, and the relationship between the operating state of the vehicle engine system and the coupled transient voltage on the power line of the ECU is analyzed. The test results show that the broadband EMP causes interference on the ECU through the power cable, and the overloaded coupling voltage resulting in the engine stalling. According to the analysis results, the multi-level protection circuit is designed for the power supply of the ECU. The electromagnetic protection is realized by cutting off the energy transmission path of the EMP threat, and the effectiveness of the protection circuit is verified.**

Keywords—ECU；EMP; transient high voltage; broadband interference; electromagnetic protection

I. Introduction

With the development of EMP related technology and vehicle electronic and electrical technology, the electromagnetic threat to vehicles becomes more prominent. On the one hand, the electrification level of vehicles is getting higher, the automatic control functions are increasing, and most of the tactical mission equipment are electromagnetic sensitive sources. The number of electrical circuits in the vehicle chassis has increased sharply, resulting in a significant increase in electromagnetic coupling paths. On the other hand, technologies such as EMP generation and radiation have been gradually applied and are developing towards miniaturization and high powered. The EMP threat to on-board electronic systems, particularly ECUs, has become a thorny problem that must be faced seriously. The high-energy EMP released instantaneously can enter the vehicle drive system through the coupling paths of the shell gaps, holes, glass, cables, etc. The peak voltage at several thousands of volts is coupled into the electronic components and causing the abnormal state of the electronic system, performance degradation, even damage, and seriously affecting the mobility of the vehicle, even the safety.

Therefore, it is necessary to analyze the EMP threats to the vehicle, implement the electromagnetic protection, and improve the safety performance of the vehicle which is under the severe EMP environment. For this, Feng Qin put forward the adaptability of the vehicle in the EMP environment and the overall protection suggestions from the system level; Zhen-Lin Yan analyzed the pattern of fuel injection signal and ignition signal of gasoline engine ECU in narrowband EMP environment, and revealed the mechanism of narrowband EMP leading to engine shutdown.

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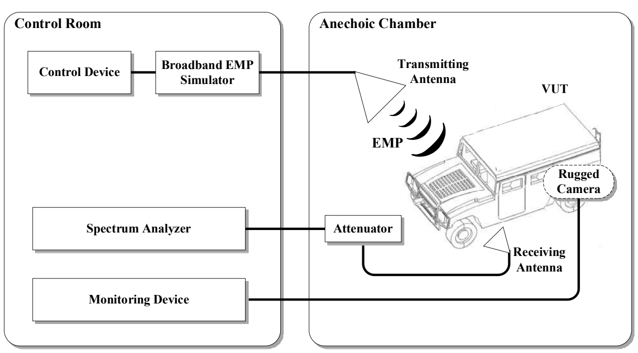
Using a certain type of High-Pressure-Common-Rail diesel engine vehicle as the object of research, a series of effect tests of broadband EMP on ECU was carried out, the EMP threat on diesel engine vehicle ECU is analyzed, and the electromagnetic protection for the power supply system of ECU is designed, and the protection performance is also verified.

II. Case Study Description

A. Phenomena

At present, the peak power of broadband EMP source has reached 100GW, the pulse repetition rate can reach 1MHz, and the rising edge (the duration from 10% to 90% of peak amplitude) is less than 1ns. Compared with narrowband EMPs, broadband EMPs cover a wider spectrum range, from hundreds of MHz to GHz, and have a high coupling efficiency for cables, which has more serious coupling effect on vehicle electrical systems with a large number of long cables.

To observe the phenomena, a simulation experiment based on an EMP simulator system and a typical tactical vehicle was carried out. The EMP environment was generated by a broadband EMP simulator and an antenna. The amplitude of this EMP was about 150kV/m to 200kV/m, the frequency band was 100 MHz - 700 MHz and the pulse width was 10 ns. The Vehicle Under Test (VUT) was running at idle speed at 750r/min. The experiment was implemented in an Anechoic Chamber, the configuration is shown in Fig.1.



In the simulation experiment, the received transient electromagnetic field strength close to the engine is between 160kV/m to 180kV/m. Once the VUT is impacted by the EMP, the engine tachometer indicator was dropped to zero value in 10s. If the indicator dropped, then the engine is stopped immediately without manual operation.

After the simulation experiment, the vehicle was inspected but no hardware failure was found. When the vehicle was restarted, the engine returned to normal. According to the above method, several repeat tests were carried out and the phenomenon was consistent. Therefore, when the VUT is in the generated broadband EMP environment, it will lose mobility and the vehicle safety will be seriously threatened.

B. Analysis

For all vehicles, the engine system is the most critical part which directly affects the first functional attribute of the vehicle. ECU is the "brain" of the engine system. It is composed of signal input unit, output unit, processing unit, and power unit. The processing unit processes input signals from a variety of sensors, outputs the driving signal, which is used to drive the fuel injection solenoid valve and rail pressure regulating valve, etc. These valves control the injecting time and amount of the fuel into the engine cylinders to maintain the engine running.

In the EMP environment, electromagnetic energy enters the engine cabin through the gaps or holes on the vehicle hull and is field-wire-coupled into the input/output cables of the ECU. Once the pulse energy induced on the cables exceeds the sensitive threshold of the internal components, the input or output signals of the ECU will be distorted, there will be random errors in digital signals. These unexpected errors can cause the ECU control instructions to execute incorrectly or fail, even cause the vehicle engine to shut down completely. The coupling paths of EMP energy on ECU is shown in Fig.2.

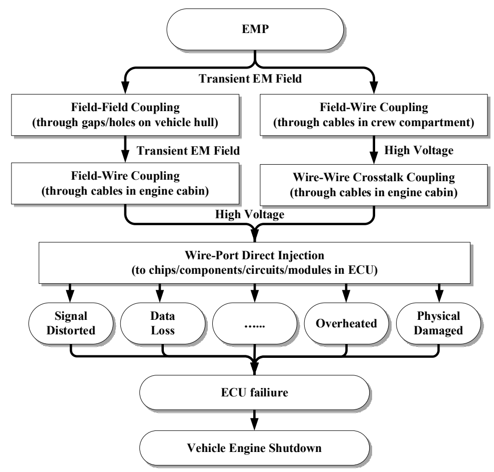


Fig. 2. The coupling paths of EMP energy on ECU.

By observing the failure phenomena and analyzing the fault code reported by the VESM, it can be seen that the error "Power Failure During Working" is caused by the abnormal power supply of the ECU. Normally, the abnormal power supply of an ECU can be classified into two situations: the external input power failure, and the internal power module malfunction.

As shown in Fig.3, the self-generating power system and battery units provide power to ECU, ABS (Anti-lock Braking System) and other modules. The ECU has two 24V power input ports, both are physically connected to the battery units through switches, and all physical switches are always on during the test. The batteries and single-use fuses are in good status. Therefore, the internal power module of ECU should be the faulty reason.

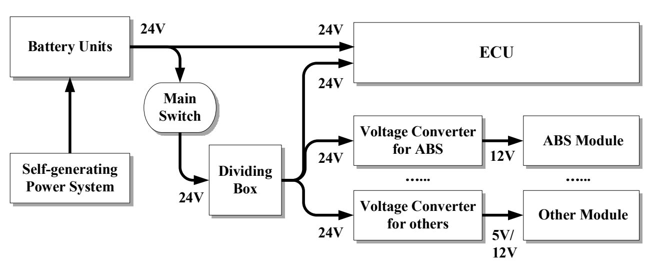


Fig. 3. The diagram of power supply in observed part of vehicle.

The ECU power module should be further considered. When the input power is insufficient or the input voltage exceeds the rated voltage range, the ECU power module will be triggered into self-protection mode and cut off the output. This potential situation results in the power failure of the ECU and the engine stalling.

The EMP energy can be coupled into the ECU power module through the ECU shell, through the power cable, and through other cables. First, the shell of ECU is an all-metal structure with good shielding, it is believed that EMP has minimum effect on the power module through the gap of the shell. Second, there is no other cables connecting to the power module except the power cable, the EMP energy can be coupled into power module in an indirect way which has relatively low coupling efficiency, so it is believed that the other cables are not considered as the main coupling path. The last one, the power cable of ECU is connected to the power module directly, and it has a length of more than 1 meter which means it is good for receiving EMP energy. Therefore, it is considered to be the main coupling path for the effect of EMP on the internal power module.

C. *Tests*

For verifying the consideration, an experiment for observing the electrical parameters and their changes on the power cable in EMP environment same as above is carried out. The configuration of this experiment is shown as Fig.4.

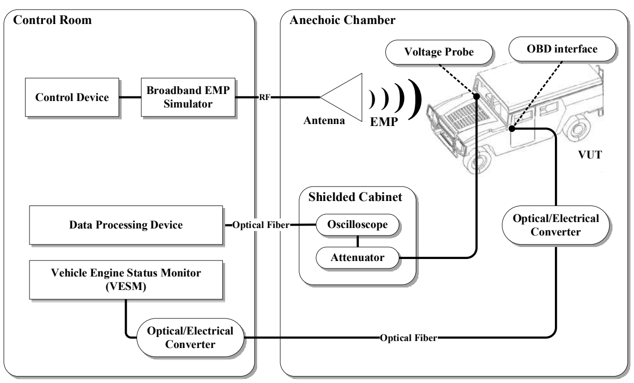


Fig. 4. The configuration of experiment for observing parameters in EMP.

During the experiment, the broadband EMP source, control device, data processing device and Vehicle Engine Status Monitor (VESM) were placed in the control room. The VUT, antenna and measurement device such as oscilloscope were placed in the anechoic chamber. To prevent the oscilloscope from being damaged by the EMP, it was placed in a shielded cabinet and connected to the ECU power monitoring interface and On-Board Diagnostics (OBD) for vehicle by optical fiber and coaxial cables. The coupling voltage on the ECU power cable and the real-time operation data of the ECU were respectively collected by the oscilloscope and the VESM.

When the VUT was exposed by the generated broadband EMP environment, the VESM reported an error "Power Failure During Working", and the engine speed data was shown as 0, then the engine stalling. The critical parameters captured by VESM are shown in Fig.5.

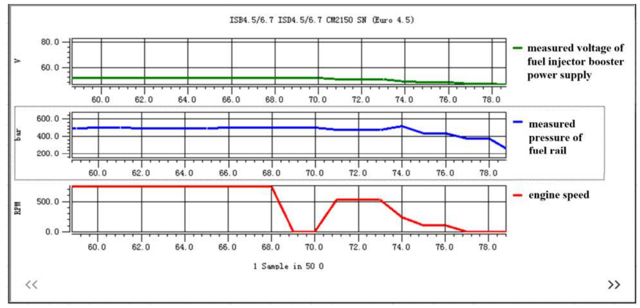


Fig. 5. Critical parameters captured by VESM in EMP impact.

At the meantime, the variation of voltage on the ECU power cable measured by probe and oscilloscope was significant, as shown in Fig.6. The peak induced voltage was 466.7V which far exceeded the maximum value accepted by ECU.

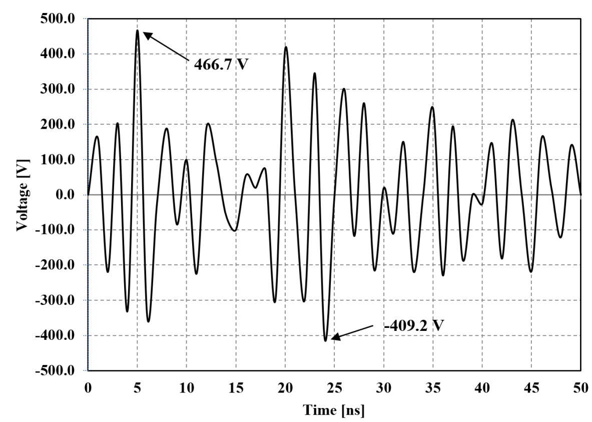


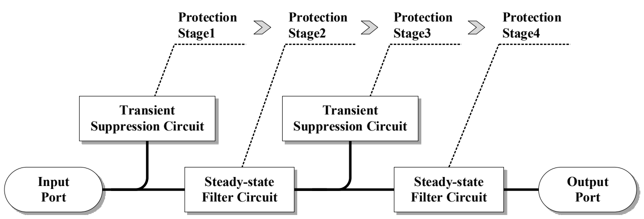
Fig. 6. Induced voltage measured on ECU power cable in EMP impact.

According to ISO7637-2, the voltage transient tolerated by the road vehicle power lines is determined by a set of test pulses. For a nominal 24 V vehicle system, the test pulses corresponding to the fast transient electromagnetic disturbance are test pulse 3a and test pulse 3b. The peak voltage U_s of the test pulse 3a ranges from -150V to -300V, the test pulse 3b ranges from +150 to +300V. As can be seen from the above test results, the peak induced voltage of broadband EMP on the power cable reaches +466.7V, far exceeding the maximum voltage tolerated by the ECU power supply. Therefore, it can be confirmed that the transient high voltage coupled into the power line will result a significant interference effect on the ECU when it's in the EMP environment, this effect will cause the ECU to stop working and the engine to stall.

III. PROTECTION SOLUTION

In view of the EMP threats faced by the ECU power module, based on the basic factors of controlling EMI (Electro-Magnetic Interference), the protection solution of cutting off the coupling path from EMP to the ECU is adopted. A multilevel protection circuit combining steady-state filter circuit and transient suppression circuit is used in the power channel to improve the electromagnetic safety performance of ECU.

The rising edge of broadband EMP is extreme short, it can be in nano-second or even pico-second level. The general protection components cannot meet the requirements of responding time. Therefore, a low-pass steady-state filter circuit is used to suppress the high frequency energy, so as to decrease the steepness of the pulse rising edge, and also reduce the pulse voltage coupled to the next stage circuit. In view of the characteristics of 24V DC power supply, the low-pass filter only considers the attenuation characteristics of high frequency amplitude and the response flatness in the passband, so the Butterworth 3rd-order low-pass filter is selected as the steady-state filter circuit. For the transient suppression circuit design, a combined circuit composes of a variety of transient energy suppression components like GDT (Gas Discharge Tube), MOV (Metal Oxide Varistor), TVS (Transient Voltage Suppressor), etc. to achieve rapid discharge of transient large current. By cascade matching of steady-state filter circuits and transient suppression circuits, the multi-level protection for ECU power supply from EMP impact is realized. The equivalent circuit of the protection module is shown in Fig.7.

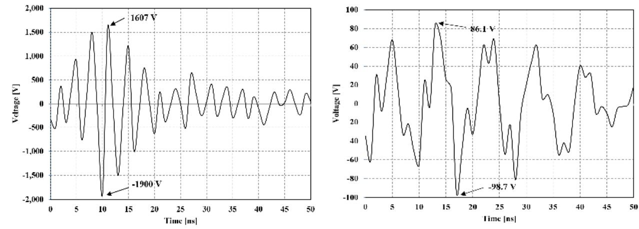


The first stage of protection is the transient suppression circuit which is a combination of MOVs and GDTs. Considering the frequent startup of the ECU power supply of the vehicle, the GDTs are connected in series to the ground terminal of the MOVs. This solution can solve the service life of the MOVs on the one hand, and on the other hand, it can prevent the leakage current generated by the MOVs causing harm to personnel.

In the second stage, a low-pass filter circuit is adopted to filter out the high frequency components of the wide frequency range EMI, and to soften the steepness of the EMP impact. The third stage consists of two transient voltage suppression diodes with low clamp voltage. They are used to shunt and isolate the pulse current, and re-discharge the residual EMP energy. The fourth stage is a steady-state filter circuit which composes of a differential mode capacitor and a common-mode capacitor. They are used to suppress the residual common mode and differential mode EMP energy on the power line.

IV. VALIDATION

The configuration of protection effectiveness validation test is consistent with initial test as shown in Fig.4. The VUT is replaced with a test-use coupling cable, which is used to inject the induced transient voltage into the input port of the protection module. In this validation test, the coupling voltage at the input port and the residual voltage at the output port of the protection module are respectively measured. After the EMP impacted, the peak coupled voltage at the input is about 1900V, the peak residual voltage at the output is -98.72V. The comparison of time-domain voltage test results is shown in Fig.8.



left: induced voltage measured at protection module input port
right: residual voltage measured at protection module output port
Fig. 8. Voltage measured at input and output ports of protection module.

To validate the practical performance of the protected ECU in the severe EMP environment, the protection module is installed in the vehicle and being well-grounded. After the test, the maximum voltage measured on the ECU power cable is 23.8V, which is far less than the value without protection. The comparison is shown in Fig.9.

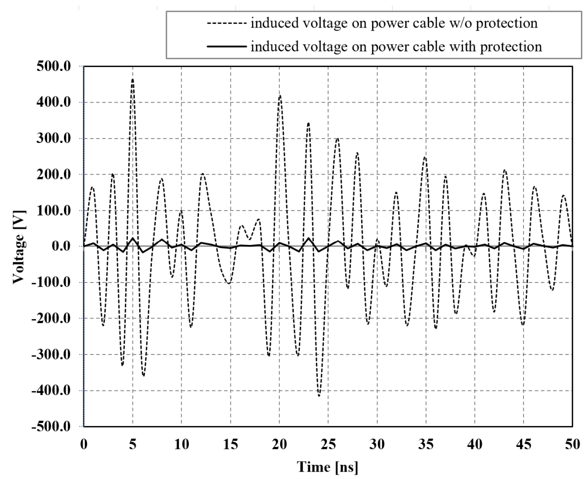


Fig. 9. Induced voltage measured on ECU power cable with protection.

By implementing the protection solution, the VUT has been tested in the EMP environment for 10 times, without engine stalling or any other abnormal phenomena.

V. CONCLUSION

With the tests of broadband EMP impact on the typical diesel vehicle, the safety threat of the vehicle under the severe EMP environment is confirmed, and the electromagnetic environmental effect of ECU is studied. Aiming at the coupled EMP energy on ECU power cable, a multistage protection circuit is designed based on the principle of steady-state filtering and transient suppression, and the effectiveness of protection is also verified. Due to the complex composition of vehicle ECU, some phenomena such as executing signal disorder and input signal deviation were also found in the research process. In order to facilitate the problem analysis, only the ECU power module was analyzed as a single sensitive unit. The next step is to carry out related effect tests and research on protection for other ECU functional modules.

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