Conceptual Design of Electromagnetic Pulse for Denied Vehicular Access Application

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Abstract. Modern vehicle architectures are complemented by the use of advanced technologies, primarily in the Engine Control Unit (ECU). This article describes the proposed conceptual design of Electromagnetic Pulse (EMP) for denied vehicular access applications, especially to vehicle (cars) engine ECU. The system mainly consists of five parts, namely power supply, magnetron, isolator, tuner, and pyramidal horn radiator. The magnetron is selected as the means for driving the pulse power generator at an operating frequency of 2.4 GHz. The pyramidal horn radiator with a gain of 15 dB is designed using CST Microwave software and fabricated as well as tested. The performance tests of the designed system are conducted in a laboratory environment and field trials, respectively. The effects of the EMP to the engine ECU are analyzed and discussed in terms of the radiated power, radiation gain, radiation pattern, and significant radiation distance. The expected target distance for stopping a vehicle is at least 3m to 5m.

1. Introduction

Electronic components, sensors, and computer systems control modern vehicle engines. Electronic devices are vulnerable to the threat of an electromagnetic pulse (EMP) because this pulse could get a couple into electronic equipment through two methods; front door coupling or back door coupling. This coupling will result in the electronic system's breakdown or destruction. Appropriately intense EMP in the 200 MHz to 5 GHz frequency range may cause damage to or upset electronic systems [1].

This phenomenon also applies to vehicles and can interfere with vehicle operation, especially engine control units (ECUs). The ECU is at the core of the Electronic Fuel Injection (EFI), which is a computerized tool used in internal combustion engines to control multiple functions in the engine, for example, to regulate the consumption of fuel and the timing of the ignition. The ECU receives data from a number of sensors in the motor and controls its performance [2]. Any disruptions to the control unit’s function can cause the engine to stall. There are several implications of this effect [3]; a car’s engine can be deactivated or stopped for slow-moving vehicles (for example vehicles being used to commit crimes such as bank robberies and drug-handovers or when there is a need to detain the occupants of a vehicle, to identifying offenders or if the driver has flouted rules on traffic), stopping vehicles at speed and to protect convoys (minimizing the possibility of vehicle assaults from collisions or gunfire). Powering vehicles may prove difficult due to problems caused by the EMP compromising the microelectronic components [4].

Using an EMP source as a weapon to stop a vehicle is a non-lethal method. EMP affects the vehicle and poses a medium risk, as EMP attacks tend only to damage electronic devices [5]. This idea is useful for law enforcement authorities and the military for protecting important events and to stop vehicles at checkpoints and in front of sensitive infrastructure. Several companies [6,7] have produced similar devices for this purpose. Several patents [8–14] have been reported for stopping or immobilizing vehicles or vessels.

In this paper, a conceptual design scheme of an EMP system based on a high-power microwave is proposed, which is used for denied vehicular access applications. Section 2 gives an overview of EMP sources and effects. Section 3 addresses the invention of electromagnetic systems for the immobilization of vehicles. The susceptibility of automotive technology to the electromagnetic environment is introduced in Section 4. Then, section 5 includes a detailed conceptual design of the proposed system. The paper's conclusions are given in Section 6.

2. Electromagnetic Pulse (EMP)

2.1. EMP Sources

Three specific EMP sources, namely the High Altitude Electromagnetic Pulse (HEMP), Ultra-Wideband (UWB) and High Power Microwave (HPM), are divided according to the delivery mechanism and operating frequency band of the pulse. Figure 1 shows the spectral density versus operating frequency ranges of various EMP as defined by IEC 61000-2-13 [15].

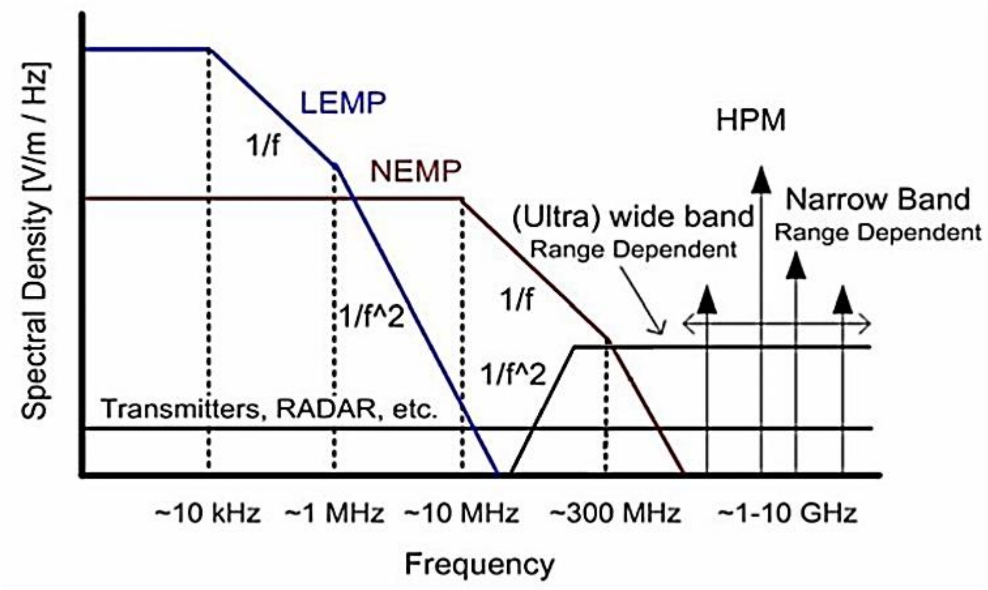

Figure 1. Typical high power electromagnetic environment (HPEM) [15].

HEMP is created when a nuclear warhead detonates at altitudes between 40 km and 400 km above the Earth's surface [16], while [17] mentioned a number above 30 km from Earth's surface. It has three stages, E1, E2, and E3. At the E1 stage, it is a free-field energy pulse calculated to increase several billionths of a second over a concise period. Such disturbances or injuries of electronic devices coincide over a large area. The E2 stage has a lightning effect in the same geographical area as E1. Although it is more widespread geographically than E1, its amplitude is weaker. E3 is a slow-rising pulse, generates interruptive currents in long power transmission lines and affects the energy supply and distribution systems connected to the lines.

UWB communication usually has a UWB pulse nanosecond with a very narrow pulse range in nanoseconds. It also has low power consumption, high-efficiency anti-interference, low complexity, low cost, and high speed [18]. Due to its frequency range and narrow pulses, it is a significant threat to electronic equipment [19].

HPM is defined as devices generating high peak microwave power (> 100 MW) at a frequency range of 1 to 300 GHz [20]. HPM and common microwave ovens differ primarily in peak power. As mentioned above, HPM has a peak power of over 100 MW [19], and microwave ovens typically consume only a few kilowatts of microwave energy. HPM energy can be transferred through directionality using a designed directional antenna to generate effects equivalent to HEMP that has a short-range or limited to a small area [20].

2.2. EMP Effect

An electromagnetic pulse (EMP) is electromagnetic radiation that occurs rapidly in a wide band and has a high intensity. It is also termed as a transient electromagnetic disturbance or electromagnetic energy that is produced in a short burst. Among the effects of EMP are large voltage and current transients which can result in an electronic system responding abnormally in terms of physical damage and upset [21]. Physical impairment is an irreversibly permanent degradation of component or system functions while upset is defined as a temporary anomalous response, which results in malfunction of digital or analog circuits and results from transients.

Electromagnetic pulses can come from natural EMP or artificial EMP. A lightning electromagnetic pulse is a type of natural EMP produced by current flow via a channel created between the cloud and the ground. Typically this discharge has a huge current flow of at least in the mega-amp range at the start, followed by a series of pulses. These pulses have decreasing levels of energy. The second example of natural EMP is electrostatic discharge, which is when two objects are charged and come into contact or are at close proximity (ESD) [22]. In contrast, artificial EMP can be generated by electric motors. The switching action of electrical circuitry creates a pulse series when the internal electrical contacts form and unform connections as the armature rotates. A power line surge is also a type of EMP. The surge can be up to several kilovolts in magnitude and can harm insufficiently protected electronic equipment. The last example is the nuclear electromagnetic pulse (NMP) from a nuclear explosion. The first nuclear event happened in 1945.

EMP damages electrical and electronics circuits through higher than tolerable voltage and currents. The threat that EMP poses to a specific system can be defined by the following factors; its frequency range (Hertz (Hz)), rise time (volts/second), and electrical field strength (volts/meter (v/m)), [23].

3. Invention of Electromagnetic Systems for Stopping Vehicles

Several companies are currently producing electromagnetic pulse systems to stop vehicles, such as Diehl BGT Defense (Germany) [6], and Teledyne e2v (United Kingdom) [7]. Diehl Defense GmbH & Co has developed a technology based on High Power Electromagnetics (HPEM) pulse called HPEMcarStop (Figure 2), HPEMcheckPoint (Figure 3), and HPEMcase (Figure 4). Meanwhile, Teledyne e2v produces three RF Safe Stop products called RF Safe Stop (Land) (Figure 5), RF Safe Stop (Sea), and RF Safe Stop Lite (Sea). A comparison of the applications and features of EMP systems in the market is shown in Table 1.

Figure 2. HPEMcarStop [6].

Figure 3. HPEMcheckPoint [6].

Figure 4. HPEMcase [6].

Figure 5. RF Safe Stop (Land) [7].

Table 1. Summary of the current electromagnetic system products for stopping vehicles and vessels in the market [6,7].

Product	Application	Features
HPEMcarStop HPEMcheckPoint	Stop moving trucks, vehicles, and motorcycles. HPEMcarStop combined with a potent source of HPEM on a trailer for stopping cars in static situations	• Target Distance - 3 to 15m • Maximum peak radiated power - 4 G Watts • Repetition rate - 60 Hz • Centre frequency - 350 MHz • Maximum burst length - 180 s
HPEMcase	Optimized for special forces to deactivate alarm systems and computers, personal checkpoints and bug clearance	• Maximum peak radiated power - 365 MW • Repetition rate - 10 Hz • Centre frequency - 350 MHz • Maximum burst length - 60 s
RF Safe Stop (Land)	Immobilizing the vehicle in the control point and convoy protection	• Stopping distance - 50m • Antenna size - 1msq
RF Safe Stop (Sea) RF Safe Stop Lite (Sea)	Harbor entry protection, maritime policing, and anti-piracy.	• Stopping distance - 50m • Antenna size - 1msq • Stopping distance - 120m • Antenna size - 1.5m x 0.75m • Weight - 156kg

Urbancokova et al. (2015) [24] discussed the US Eureka Aerospace Corporation, whose use of microwave and radio frequency (RF) technology is similar to electronic triggers for stopping vehicles, ships, and eliminating improvised explosive devices. The system consists of a Marx generator, which can operate at a distance of 200 m from 350 MHz to 1.35 GHz. The EMWS engine stopper developed by Fiore Industries Inc (USA) was discussed by [24] and is capable of generating a pulse width of 2.4 kW, 30 µsec, and has a pulse repetition frequency of 8 kHz. The system is made up of several pulse amplifiers that are routed to their respective antenna elements and controlled remotely.

Valouch and Urbančoková (2016) [3] proposed a novel idea to automatically control the generator by integrating it with an alarm system and using a camera system that is able to identify the vehicle type and speed. Since 1994 [8–13], there have been several patents concerning vehicle stopping or anti-theft devices, which were invented using different concepts and designs. The latest invention [13] uses a magnetron to provide a 5 MW output power at a frequency of 3 GHz. up to 23 vehicle samples from 14 different manufacturers were tested by [13] with a peak power ranging from 1 MW to 5 MW, and a success rate of 80% was achieved. However, the author did not mention the antenna type and the working distance of the system.

4. Susceptibility of Automotive Technology to Electromagnetic Environment

The question of EMP damage to a vehicle is a complex one and its answer depends upon details such as the location and position of the car when the EMP happens. The effect of EMP caused by lightning on the electronic systems of a vehicle has been the subject of several experimental works and has been previously reported [25]. A report in [26] shows a total of 37 cars had been tested in an EMP simulation laboratory under both engines turned off and turned on conditions. Based on the test results, no effect was subsequently observed for automobiles with non-running engines. However, the most serious effect was observed on running vehicles when the motors stopped at a field strength of approximately 30kV/m. In [2], effective distance, the influence of exposure time, vehicle orientation and speed influenced the tests which were conducted. Tests were conducted on up to eight different vehicles and the most successful distance was within five meters.

The specification for electromagnetic immunity requirements of automotive technology must be evaluated during the design process. Electronic circuits normally operate below a supply voltage of -5 Volt [6]. There are several studies [1,22,27–29] that observed the effects of EMP on the semiconductor chip and microprocessor board. The effects of EMP were analyzed based on the significant distance of transmitted EMP to the target circuit board. Several effect factors such as operating frequency, burst rate, pulse duration, radiation pattern, and entry point were also investigated and discussed.

5. Conceptual Design

The designed system mainly consists of five parts, namely power supply, magnetron, isolator, tuner, and pyramidal horn radiator. The magnetron-based generator is selected as the means for driving the pulse power generator at an operating frequency of 2.4 GHz. The pyramidal horn radiator with a gain of 10 dB is designed using CST Microwave software and fabricated, as well as tested. The performance tests of the designed system will be conducted in a laboratory environment as well as field trials. The block diagram of the microwave-based EMP system is shown in Figure 6.

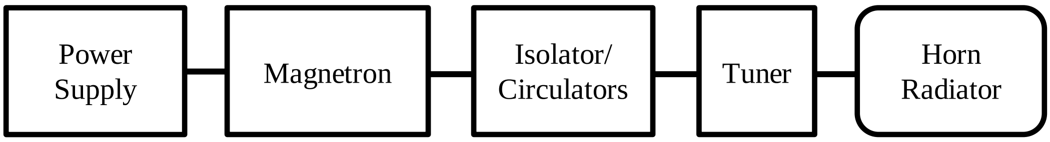

Figure 6. Block diagram of the microwave-based EMP system.

A DC power supply is used to provide voltage and current to power the magnetron. They include a capacitor diode and a transformer (high voltage and filament). Compared with switching or pulsed power supplies, the advantages of DC power supplies are simplicity and low cost. The microwave power is generated from an air-cooled magnetron with a DC input of 0 to 3 kV to drive a pulse generator.

The output of the magnetron is connected to a waveguide isolator. This isolator is used to protect the magnetron from reflected microwave energy and provides a matched load to the magnetron for effective microwave energy generation. The manual waveguide tuner will feed into the isolator; which is used for impedance matching to achieve a coupled matching of propagated wave in the cavity waveguide by adjusting the metal stub depth at different guide lengths. This reduces reflected power and maximizes the coupling power to the pyramidal horn radiator. The standard waveguide WR340 is used because of its operating frequency covering the ISM band (2.45 GHz).

The waveguide tuner is connected to a pyramidal horn radiator, which is an essential part of this design system. The performance and efficiency of the horn radiator determine the gain and distance of the transmitted microwave. Due to the simple structure of the horn radiator, ease of excitation, large gain, low sidelobe, low return loss, and broad bandwidth, this type of radiators are used in many applications [26, 27]. Many researchers have used different techniques to optimize the horn radiator for better performance [31]. In recent research, [32–34] used a metasurface lens, and graphene sheets are mounted on the radiator wall to gain enhancement and reduce the sidelobe level. The pyramidal horn radiator with a gain of 15 dB and 20^o of 3-dB beamwidths are designed using CST Microwave software and fabricated as well as tested using vector network analyzer. The designed horn radiator is expected to have a low VSWR value of 1.15 at 2.45 GHz. In order to obtain those performances, the cavity of the posterior horn is proposed to be filled with a dielectric material to enhance the intensity of the radiated electrical field at the horn aperture. On the other hand, the performance tests of the proposed designed system will be conducted in a laboratory environment and field trials.

6. Conclusions

The proposed, designed system can be used to stop vehicles at checkpoints, building complex entrances, and at the entrances to vital installations by law enforcement authorities and the military as a non-lethal approach. The expected target distance for stopping a vehicle is at least three to five-meter.

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