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Vehicle-level Analysis Technique for EMC Design of Automotive Inverters

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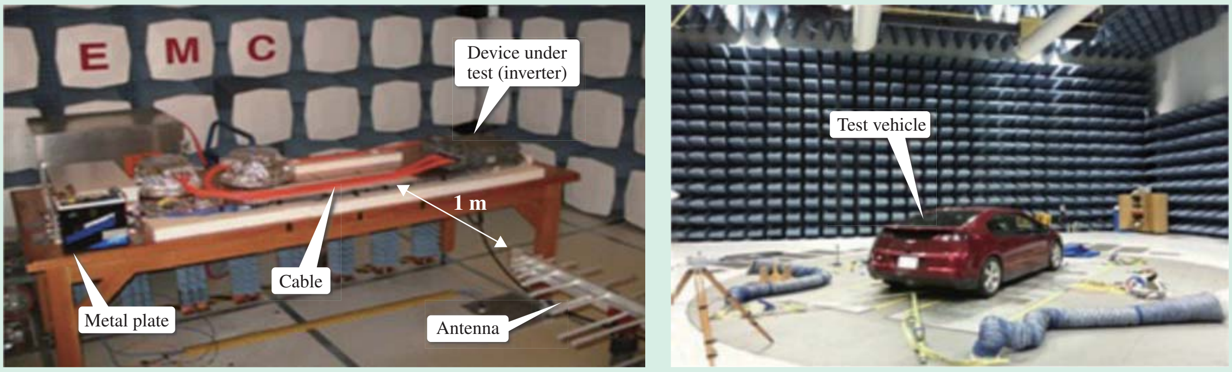
OVERVIEW: To ensure vehicle safety and comfort, there is a need to minimize interference due to electromagnetic noise from automotive electronics. While automotive manufacturers have stipulated EMC standards for this purpose that component suppliers are obliged to comply with, there are cases when additional measures are needed to satisfy EMC requirements for the vehicle as a whole even though its individual components comply with the EMC standards, as the behavior of electromagnetic noise varies depending upon the installation conditions. This happens because the amount of noise generated changes when the electronics components are installed onboard. In response, Hitachi has developed a vehicle-level analysis technique that can predict electromagnetic noise for the completed car in which the electronic components are installed, thereby enabling EMC countermeasures to be incorporated into the design at an upstream design level, rather than added reactively. To enable the technique to predict the level of noise with sufficient accuracy for use in design (within ±12 dB), it splits the vehicle analysis into three separate parts in order to reduce the dynamic range that each one needs to deal with, thereby making it possible for the full analysis to deal with the wide dynamic range in the level of electromagnetic noise detected by a vehicle-mounted antenna, from the drivetrain inverter with a high power output (kW) down to tiny µW-level radiation. By adopting this approach, Hitachi believes it can successfully perform EMC design for the completed vehicle at the component design stage.

INTRODUCTION

THE number of electronic components used in vehicles has increased over time along with greater electrification and technical progress in data network connectivity. To ensure that the electromagnetic noise generated by these components does not interfere with the operation of other devices, such as car radios, manufacturers of automotive electronics conduct electromagnetic compatibility (EMC) testing of individual components and vehicle manufacturers conduct testing of completed vehicles[(1), (2)].

Fig. 1 (left) shows an example of EMC testing of an automotive inverter. The test determines the level of radiated emissions by placing the inverter, cable, and other components on a metal plate that simulates the vehicle chassis and measuring the voltage induced in an antenna positioned nearby. Test conditions such as the position of the cable and measurement antenna are stipulated in the International Special Committee on Radio Interference 25 (CISPR 25) international standard. In the case of radiated emissions testing, for example, this specifies measuring the induced voltage in an antenna placed 1 m from the cable. Vehicle testing, in contrast, is performed using a production-model vehicle (see Fig. 1 right). Vehicle EMC testing is broadly divided into radiated emissions testing that measures the induced voltage in an antenna positioned outside the vehicle, and interference testing on vehicle-mounted antennas such as that used by the car radio. In these tests, however, the conditions for the generation and propagation of electromagnetic noise differ widely from vehicle to vehicle due to factors such as antenna location and vehicle body shape. Although careful study is undertaken before performing standalone EMC testing of components in order to replicate actual onboard installation conditions, the EMC behavior still does not necessarily match that on the actual vehicle.



EMC: electromagnetic compatibility

Fig. 1—EMC Testing of Automotive Electronics (Left) and Vehicle (Right).
EMC testing of electronic components is performed using a cable and antenna in accordance with a standard. As vehicle testing uses a production-model vehicle, the conditions for the generation and propagation of electromagnetic noise differ from vehicle to vehicle and therefore the results do not always match those of individual component testing.

Consequently, even if a component itself passes EMC testing, there is a risk that electromagnetic interference problems will still be found on vehicle-mounted antennas during vehicle EMC testing. Because vehicle EMC testing is not normally performed until after component testing, if it turns out that modifications are needed, this imposes additional costs or delays due to design changes to the component or vehicle. This results in considerable losses not only to the automotive electronics manufacturer but also the vehicle manufacturer.

In response, Hitachi has worked with General Motors Company (GM) in the USA to develop an EMC analysis model for completed vehicles (including the inverter) that can be used to predict the level of electromagnetic noise from electronic components onboard. The work included verification testing on actual vehicles. The ability to predict—at the component design stage—the level of electromagnetic noise that those components will emit when installed in the vehicle makes it possible to produce low-noise designs (see Fig. 2). The research was targeted at use on GM's electric vehicle Volt that is equipped with two motors, high-voltage batteries, high-voltage shielded cables that connect to the batteries, and a drivetrain inverter that is made by Hitachi. The model was suitable for analysis of the electromagnetic noise from the inverter installed in the vehicle.

MECHANISM OF ELECTROMAGNETIC NOISE GENERATION BY INVERTER

The drivetrain inverter in a hybrid electric vehicle uses switching of insulated-gate bipolar transistors (IGBTs) or similar semiconductors to convert several hundred volts of direct current to the alternating current that drives the electric motor. Although the semiconductors operate at a switching frequency in the order of kHz, the

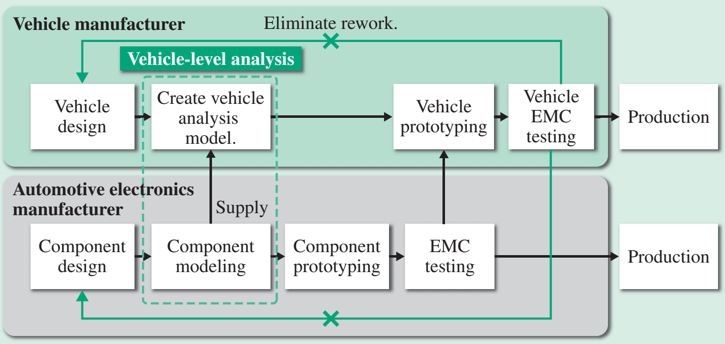


Fig. 2—Development Process for Automotive Electronics and Vehicles.
Because vehicle EMC testing is not performed until after component EMC testing, any problems with noise result in additional costs and delays due to design changes.

high-frequency components generated during voltage switching extend up to the MHz range. Furthermore, whereas an inverter has an output in the kW range, because preventing interference due to the leakage of electromagnetic noise requires that this noise level be considerably low (in the μW range or less), it is standard practice to use shielded cables for connecting between the inverter, motor, and high-voltage batteries.

VEHICLE-LEVEL EMC ANALYSIS

The technical challenge posed by vehicle-level EMC analysis is to conduct a precise analysis over a wide dynamic range that extends from the high-power (kW range) operation of the inverter to very low levels of radiated emissions (μW range). The difficulty is that an analysis over this wide dynamic range needs to be accurate over nine orders of magnitude (180 dB), which is difficult to achieve through normal analysis of this nature that deals with only three orders of magnitude (60 dB). Accordingly, a sequential vehicle-level analysis was developed to overcome this problem based on an assumed mechanism whereby radiated emissions are generated by leakage currents in the vehicle body[(3)]. This involved improving accuracy by dividing the analysis into three stages in order to minimize the dynamic range that each analysis needed to deal with: (1) inverter switching analysis, (2) leakage current analysis, and (3) radiated emissions analysis (see Fig. 3).

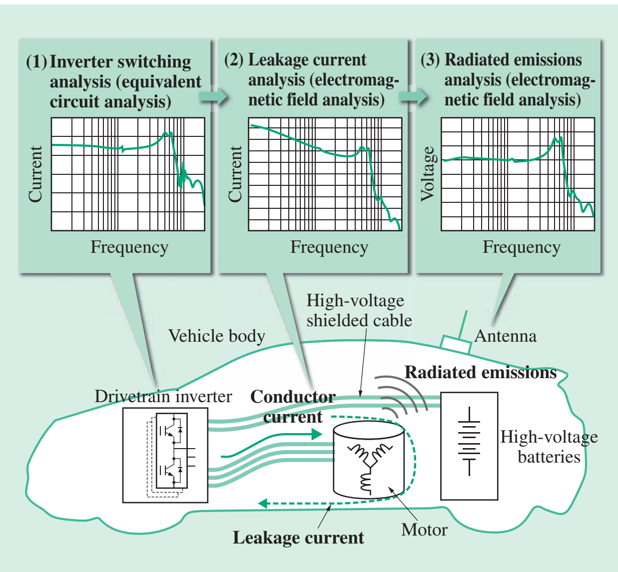


Fig. 3—Vehicle-level Analysis.
A high level of accuracy is achieved by splitting vehicle-level analysis into three parts.

The following section describes these separate analyses. First, an equivalent circuit analysis is used to calculate the high-frequency components (I_N) of the motor drive current output by the inverter. Next, electromagnetic field analysis is used to calculate how much of the high-frequency current (I_N) generated by the high-speed inverter switching leaks to the vehicle body. As the leakage current distribution is determined by the shape of the metal in close vicinity to the cable, the analysis only covers this narrow region. This determines the proportion (K_1) of the inverter output current that leaks to the vehicle body (leakage current coefficient). The third step is to determine the level of interference at the antenna due to electromagnetic noise generated by the leakage current in the vehicle body. This is done using an electromagnetic field analysis of the propagation of noise inside and outside the vehicle and the antenna induced voltage, treating the leakage current as the excitation source. This analysis provides the radiated noise propagation coefficient (K_2) from the leakage current to the vehicle-mounted antenna. By using these analyses to obtain the inverter output current (I_N), leakage current coefficient (K_1), and noise propagation coefficient (K_2), the induced voltage in the vehicle-mounted antenna (V_A) can then be calculated (equation 1).

$$V_A = I_N \times K_1 \times K_2 \qquad (1)$$

By focusing on the known mechanism whereby radiated emissions are generated by the high-frequency leakage current, and by separating the vehicle-level analysis into parts, the dynamic range of power levels dealt with by each analysis is kept below three orders of magnitude (60 dB). This enables a high-precision analysis to be performed using standard electromagnetic field analysis software. Furthermore, if a design change consists of shifting the antenna only, it is sufficient to only re-perform the analysis for the noise propagation coefficient (K_2). Accordingly, this approach also improves the efficiency of the analyses, which need to be performed numerous times during the early design stage.

Fig. 4 shows the vehicle model used for the noise propagation coefficient (K_2) analysis. A monopole EMC testing antenna is used for testing. Meanwhile, to verify that the method is suitable for vehicle-level analysis, analyses were performed for two separate antenna locations (on the roof and on the front of the vehicle) and the results compared with actual measurements.

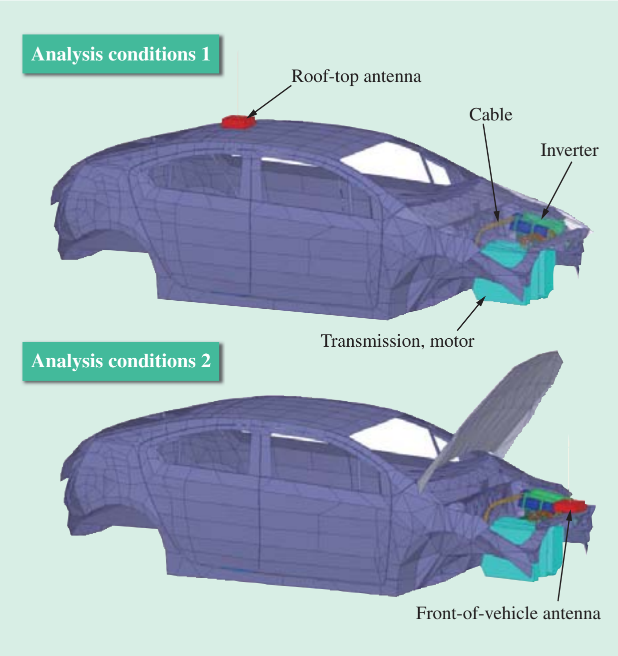


Fig. 4—Radiated Emissions Analysis Model.
The vehicle-level analysis was performed for two antenna locations to perform analytical verification of the induced voltage due to noise at different antenna locations.

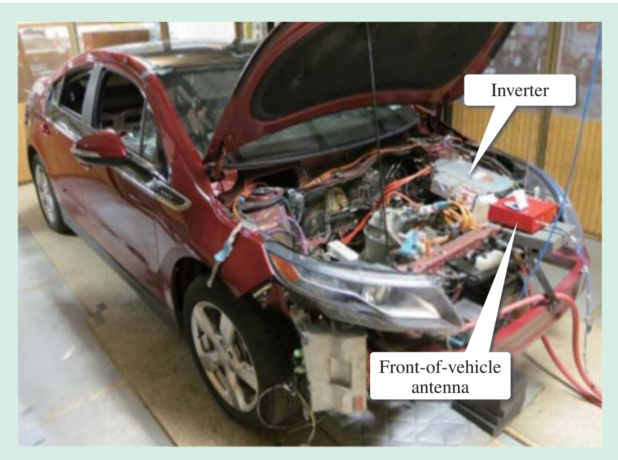


Fig. 5—Specially Prepared Vehicle for EMC Measurement.
The voltage induced in the antenna during inverter operation was measured on an actual vehicle.

MEASUREMENT

Fig. 5 shows the vehicle that was specially prepared for conducting the electromagnetic noise measurements by removing electronic components other than the drivetrain inverter that was the subject of the test. This was done to prevent noise from these other components from influencing the results. The antenna for measuring radiated emissions was positioned at the same locations as in the analysis (on the roof and on the front of the vehicle) and the induced voltage in the antenna measured using special-purpose test equipment. All measurements were performed in a shielded room to prevent disturbances due to external noise.

PREDICTED VS. ACTUAL RESULTS AND DISCUSSION

A comparison was made of the predicted and actual results for the frequency characteristics of the induced voltages measured at the two antenna positions (see Fig. 6). The peak noise frequency was 6 MHz when the antenna was located on the roof and 7 MHz when it was on the front of the vehicle, with errors between predicted and measured values of 3 dB and 7 dB at the two respective frequencies indicating good agreement. Possible causes of error in the high-frequency range above 10 MHz include simplification of the vehicle.

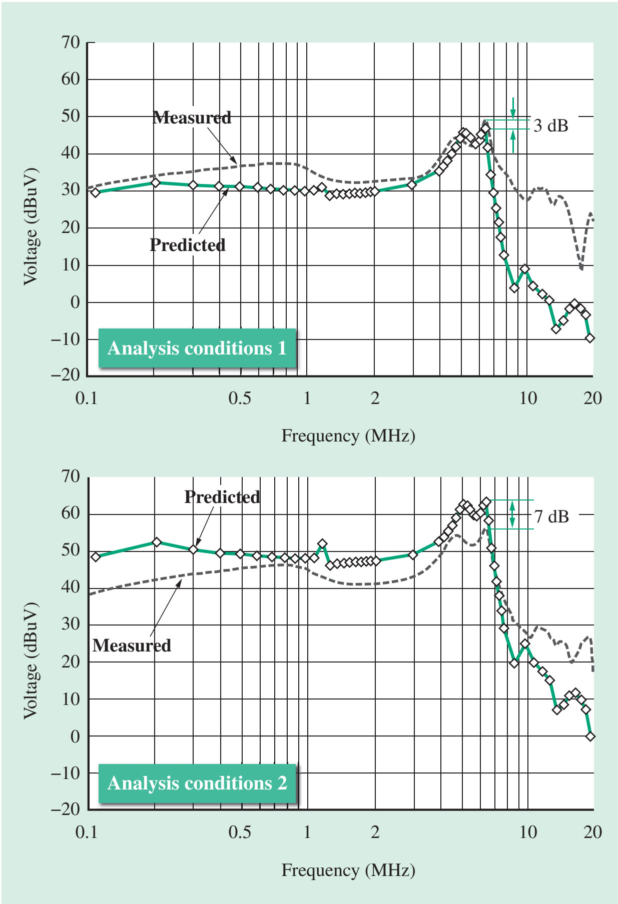


Fig. 6—Comparison of Analysis and Measurement of Radiated Emissions.
The comparison indicated an error in the predicted maximum noise levels of approximately 7 dB, and confirmed the frequency characteristics of the antenna induced voltage and the differences in induced voltage due to location.

Furthermore, in the case of vehicle-level analysis, it is important to verify the accuracy of both the noise source and vehicle models because the errors due to these are added up.

CONCLUSIONS

Hitachi has developed a vehicle-level EMC analysis technique so that countermeasures against electromagnetic noise can be built into automotive electronics in the upstream stage of design process. Although the analysis covers a wide dynamic range (180 dB), predictions of the level of interference at vehicle-mounted antennas can be made with sufficient accuracy for practical component design (within ±12 dB) by splitting the analysis into three parts to minimize the dynamic range dealt with by each part. In the future, Hitachi intends to make use of this new technique in the EMC design of electronic components.

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