Novel injection methods for substitution of irradiation under different coupling routes of electromagnetic interference

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Abstract. At present, the maximum electromagnetic radiated field strength which can be simulated is not able to satisfy the requirements of electromagnetic environment effects tests on electronic systems. To broaden the effective frequency range of the current injection technique, new current injection methods were put forward for substitution of the radiation. A wide-band current injection device was designed based on the symmetric directional coupler principle. With a typical antenna receiving system under test, the validity of the methods were analyzed by theory and verified by experiments when the Equipment Under Test (EUT) had different coupling routes of electromagnetic interference (EMI). The results indicate that: firstly, the relationship between radiated fields and injected voltage is linear, even if the responses of the system are non-linear; secondly, the method is valid even if the test frequency is up to gigahertz; thirdly, the novel methods of current injection are able to substitute for irradiation effectively when the antenna and the interconnected cable are the main coupling routes of EMI respectively.

1. Introduction
With the appearance of electromagnetic pulse (EMP) weapons, electronic systems suffer from a quite worse electromagnetic (EM) environment. So there is a corresponding increase in electromagnetic compatibility (EMC) clearance levels. The need to test these systems at higher levels is posing great problems for test community, because the levels of radiated strength simulated by laboratories are limited. As an alternative to the standard radiated field susceptibility test, current injection has been researched for many years. Bulk current injection (BCI) technique is widely used for interconnected systems. However, BCI test is proved to be effective for frequencies below 400MHz [1-4]. Above 400 MHz, errors are significantly increased and test results become sensitive to the position of the probe [5-7]. At present, the operating frequency of many electronic systems such as some radar and communication systems is up to gigahertz. Hence, in order to broaden the current injection technique’s effective frequency range, new current injection methods should be put forward.

2. Relationship between radiated field strength and injected voltage
In general, radiation and injection cannot be made equivalent in the strict sense for interconnected systems. This stems from the fact that radiated fields give rise to distributed coupling along the length of the cable, whereas injection devices act as lumped sources of voltage. However, as the equipment attached to the cable ends is the real victims of electromagnetic (EM) disturbance, it is an

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appropriately equivalent method to ensure that the injection-induced noise currents at the ends of cable are equal to the radiation-induced noise currents. Considering the limitations of the BCI technique, new current injection method is put forward based on the differential mode coupling principle. Symmetric directional couplers are used as injection device. The test system employing this device is sketched in figure 1. Equipment A and B is auxiliary equipment (AE) and EUT respectively, and they are connected by coaxial cable. Ports from 1 to 4 of directional coupler are the input port, transmitted port, coupled port and isolated port, respectively. The current source attached to port 4 is employed to inject noise current into equipment B.

![Figure 1. Block diagram of system for current injection.](image)

If the response of equipment B is concerned only, the Thevenin equivalent circuits of the system for radiation and injection can be seen in figure 2 and 3 respectively. $U_{SR}$ and $U_{SI}$ represent the equivalent voltage source for radiation and injection. $Z_{SR}$ and $Z_{SI}$ represent the corresponding equivalent source impedance. $Z_{SR}$ equals to $Z_{SI}$ since the entire system for radiation and injection are the same. Namely,

$$Z_{SR} = Z_{SI} = Z_0 \frac{1 + S_{12}^2 \Gamma_A e^{-2\gamma L}}{1 - S_{12}^2 \Gamma_A e^{-2\gamma L}} \tag{1}$$

where $S_{12}$ is the scatter parameter of directional coupler, $Z_0$ and $L$ denote the characteristic impedance and the length of the coaxial cable respectively, and $\Gamma_A$ is the reflection coefficient of equipment A. According to the Thevenin theorem, the responses of equipment B are equal for radiation and injection if $U_{SR}$ is equal to $U_{SI}$, no matter whether the response of EUT is linear or non-linear. The way to ensure the equivalence between $U_{SR}$ and $U_{SI}$ is to make the responses of EUT equal by adjusting the current source. The process of electromagnetic field coupling to antenna and cable is linear, as well as the coupling process of directional coupler. Due to this fact the relationship between the electric field strength $E$ and the injected voltage $U_C$ is also linear. Namely, the proportional coefficient $k = \frac{U_C}{E^{-1}}$ is constant. On account that the levels of electric field strength can be simulated is limited, the value of injected voltage equivalent to high level electric field strength should be linearly extrapolated. By this means the current injection method can substitute for high level field illumination equivalently. So the entire test procedures are as follows: (1) obtain the output voltage of equipment B $U_B$ through low level field radiation test at electric field strength $E_1$; (2) adjust the output voltage of current source $U_1$ to impose equivalence between $U_B$ and the output voltage of equipment B in the injection test; (3) calculate the proportional coefficient $k = \frac{U_1}{E_1^{-1}}$, repeat aforementioned procedures at other levels electric field strength, and obtain the average value $k_{av}$ of the proportional coefficient $k$; (4) if the radiation experiment is carried out at higher levels of electric field strength $E_2$, the corresponding injected voltage $U_2$ yields $U_2 = k_{av} E_2$, and the output of the system in the injection experiment is...
equivalent to that in the radiation experiment with electric field strength $E_2$.

![Figure 2. Equivalent circuits of radiation.](image1)

![Figure 3. Equivalent circuits of current injection.](image2)

In order to demonstrate the validity of the above-mentioned theoretical analysis, a receiving antenna and a low-noise amplifier (LNA) were employed as the equipment A and B respectively. They were connected with a 9-m-long RG-58 coaxial cable. The antenna and LNA are typically linear and non-linear equipment respectively. A symmetric directional coupler was used as the injection device. Connect the whole system according to figure 1, the output of equipment B was connected to spectrum analyzer. Radiation experiment was finished in an open area test site. The antenna and coaxial cable are in the radiation area except the equipment B. The aim is to ensure the input port of equipment B is the only way for the interference current to enter into the equipment. The working frequency band of the whole system is from 2 to 8 GHz. 4.6 and 7.2 GHz were chosen as the test frequency points. A horn antenna was chosen as the transmitting antenna which was vertically polarized. The experiment was carried out according to the aforementioned procedures.

![Figure 4. Output voltage of LNA and injected voltage with different radiated fields strength.](image3)

The relationship between the output voltage of LNA and the electric field strength is illustrated in figure 4. The figure also plots the injected voltage versus the electric field strength when the output voltages of LNA are equal for radiation and injection. As shown in figure 4, the relationship between the output of LNA and the electric field strength is typically non-linear. However, at the same time, the curve of the injected voltage versus the electric field strength is linear. Perform straight-line fitting for the latter curve. The results show that the coefficient of determination is 0.999 for both 4.6 and 7.2 GHz. Accordingly, the proposed equivalent methods are able to reproduce radiation-induced effects even if the EUT is nonlinear. In addition the BCI test is based on the injection of common-mode noise...
currents in the cable. Hence, it cannot substitute for radiation if the interference is differential-mode noise currents just like this experiment. However, this injection method which is able to inject differential-mode currents can solve this problem well, as demonstrated by the experimental results.

3. Equivalence with different coupling routes of EMI
Aforementioned analysis has demonstrated the equivalence between radiation and injection when the antenna is the main coupling route of EMI. Additionally, the cable is another main coupling route. Hence, in this situation, the question whether this injection method can substitute for radiation equivalently or not should be studied, especially for coaxial cable. When considering shielded cables, the noise currents induced at the terminal units by distributed field coupling can be directly related to the current and voltage distribution along the external surface of the cable. It seems to be different from the new injection methods which inject noise currents into the terminal units directly.

For the interconnected system as seen in figure 1, the left side of equipment B can be modeled as nonideal voltage generators (i.e., series connection of ideal voltage generators $U_S$ and internal source impedance $Z_S$) if the response of equipment B is concerned only. As shown in equation (1) $Z_S$ equals to $Z_{SR}$. According to the BLT equations and Thevenin theorem [8], the equation (2) and (3) can be obtained.

$$U_{1S} = \frac{2(e^{-\gamma L} S_1 + \Gamma e^{-2\gamma L} S_2)}{1 - \Gamma e^{-2\gamma L}} \quad (2)$$

$$\Gamma_{1S} = \Gamma e^{-2\gamma L} \quad (3)$$

where $U_{1S}$ and $\Gamma_{1S}$ are the equivalent ideal voltage generators and source impedance at the left side of port 1. Hence, $U_S$ yields

$$U_S = \frac{2S_{12}(e^{-\gamma L} S_1 + \Gamma e^{-2\gamma L} S_2)}{1 - S_{12}^{2}\Gamma e^{-2\gamma L}} \quad (4)$$

Consequently, it is feasible to substitute injection for radiation in this situation since the response of equipment B is able to be seen as the effect of a lumped voltage generator.

![Figure 5. Output voltage of equipment B for radiation and injection with cable as the main coupling route.](image)

In order to assess the aforementioned analysis, an experiment was carried out. The test setup is as follows. The system under test was the same as that shown in figure 1. The coaxial cable was placed in the shielded room to ensure the cable was the only way to couple EM interference. The remaining
parts were placed outside of the shielded room and connected to the coaxial cable through connectors on the wall of the shielded room. Equipment A and B were a receiving antenna and radio frequency front-end respectively. The cable was illuminated by a horn antenna in the shielded room. The experiment was performed according to the aforementioned procedures. 4.5 GHz, 5.5 GHz and 6.5 GHz were chosen as the test frequency points. The results are shown in figure 5. For simplicity, the abscissa of the injection experiment’s data curve is the electric field strengths which are equivalent to the corresponding injected voltages. The mean errors of equipment B’s output voltage for radiation and injection are 0.8%, 0.71% and 0.49% for 4.5, 5.5 and 6.5 GHz respectively. The results indicate that the injection method in this paper can substitute for radiation even if the cable is the main coupling route of EMI. It also shows that the noise currents injected into the terminal units are differential-mode interference. This fact makes it possible for the proposed equivalent scheme to substitute for radiation.

4. Conclusion
In this paper, a new current injection method substituting for radiation has been developed and discussed. The proposed methods are aimed at broadening the current injection technique’s effective frequency range. The results indicate that the equivalent relationship between radiated field strength and injected voltage is linear for interconnected systems even if the responses of the system are non-linear. Secondly, the method can substitute for radiation equivalently even when the frequency is up to gigahertz. Thirdly, the method is valid when the antenna and coaxial cable are the main coupling route of EMI respectively. It has no problems in representing the stresses that will be seen on the internal cores of the cable. The mean errors of the EUT’s outputs for radiation and injection are less than 2%. It proves the validity of the proposed methods.

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