Mode decomposition of conducted noise voltage with synchronized vector signal measurement

Kei Hayashi\(^a\), Shunji Mori, Takaaki Ibuchi, and Tsuyoshi Funaki

Osaka University, Div. of Electrical, Electronic and Information Eng.,
Graduate School of Engineering, Suita 565–0871, Japan
\(^a\) hayashi@ps.eei.eng.osaka-u.ac.jp

Abstract: This paper proposes an evaluation method for common mode (CM) and differential mode (DM) of conducted emission in the power line measured with a Vector signal analyzer (VSA). The termination disturbance voltage of the two LISN (line impedance stabilization network) are synchronously measured with a 2ch VSA. The results of vector signal processing in the proposed method in experimentally validation by comparing with the results of conventional method for noise mode separation by using CMDM switch.

Keywords: vector signal analyzer, common mode, differential mode, mode decomposition

Classification: Electromagnetic Compatibility (EMC)

References

[1] T. Kim, D. Feng, M. Jang, and V. G. Agelidis, “Common mode noise analysis for cascaded boost converter with silicon carbide devices,” \textit{IEEE Trans. Power Electron.}, vol. 32, no. 3, pp. 1917–1926, Mar. 2017. DOI:10.1109/TPEL.2016.2569424

[2] S. Wang, F. C. Lee, and W. G. Odendaal, “Improving the performance of boost PFC EMI filters,” Eighteenth Annual IEEE Applied Power Electronics Conference and Exposition (APEC2003), vol. 1, pp. 368–374, 2003. DOI:10.1109/APEC.2003.1179240

[3] M. C. Caponet, F. Profumo, L. Ferraris, A. Bertoz, and D. Marzella, “Common and differential mode noise separation: Comparison of two different approaches,” IEEE 32nd Annual Power Electronics Specialists Conference, vol. 3, pp. 1383–1388, 2001. DOI:10.1109/PESC.2001.954313

[4] CMDM 8700 data sheet (http://www.schwarzbeck.de/Datenblatt/k8700.pdf).

[5] W. Fan, A. Lu, L. L. Wai, and B. K. Lok, “Mixed-mode S-parameter characterization of differential structures,” Proc. 5th Electronics Packaging Technology Conference (EPTC 2003), pp. 533–537, 2003. DOI:10.1109/EPTC.2003.1271579
1 Introduction

High frequency switching operation of power semiconductor devices are required for miniaturizing power conversion system. The fast switching operation of power device is necessary for higher frequency operation of the circuit. High $di/dt$ and $dv/dt$ in the transient response of power device induces significantly large and wide band noise spectrum [1, 2]. Differential mode noise, which is accompanied with switching operation of power device, is unavoidable in the normal operation of power conversion circuit. It can be sufficiently suppressed by filter in the circuit. Common mode noise does not emerge from ideal circuit condition. However, an asymmetry of circuit (circuit topology, parasitic capacitance and inductance of circuit component) converts differential mode noise to common mode noise. The common mode conducted emission significantly induces radiated emission as EMI (electromagnetic interference). Therefore, measurement and evaluation of common mode components of conducted emission is important to assess EMC (electromagnetic compatibility) performance of power electronics circuit.

The conducted emission is evaluated as the frequency spectrum of terminal disturbance voltage LISN (line impedance stabilization network) as standardized in CISPR 22 and 11. $\Delta$-type LISN or CMDM mode switch (CMDM switch) is used to directly evaluate common mode (CM) and differential mode (DM) in the measurement of conducted emission [3, 4]. CMDM switch decomposes two input signals into CM or DM. This paper presents usage of vector signal analyzer (VSA) for mode decomposition of conducted emission voltage. Frequency spectrum of CM and DM voltage are obtained by vector calculation of two synchronously operated VSA output. The performance of the proposed decomposition is experimentally evaluated and compared with the results from conventional CMDM switch.

2 Mode decomposition

This section addresses the mode decomposition of conducted emission voltage with conventional CMDM switch, and the proposed method with synchronous measurement of two VSAs.

2.1 Mode decomposition with CMDM switch

The CMDM switch (9 kHz–30 MHz/CMDM8700/SCHWARZBECK) decomposes conduction noise voltage measured with V-type LISN of each power line into common or differential mode voltage. Figs. 1(a) and (b) shows the frequency characteristics of mode separation performance to the sinusoidal input. $S_{sc12}$ and $S_{sd12}$ in Figs. 1(a) and (b) respectively shows the transmission gain for common and differential input [5]. The decomposed mode component corresponding with the input signal mode given as $S_{sc12}$ and $S_{sd12}$ are transmitted without attenuation 0 dB over entire frequency range of the conducted emission standards. $S_{sd12}$ and $S_{sc12}$ in Figs. 1(a) and (b) show residual component for differential mode input signal. 40 dB rejection ratio is achieved for frequency lower than 10 MHz. The rejection ratio deteriorates with increasing frequency for higher than 10 MHz. CMDM switch has 32 dB rejection ratio both in common and differential mode at 30 MHz.
2.2 Mode decomposition by vector signal processing

The mode rejection ratio of CMDM switch is used as the reference of following proposing mode decomposition method. VSA decomposes input signal frequency spectrum into component in-phase $I$ and quadrature component $Q$. Vector calculation of 2 input signals A and B is possible, when they are synchronously measured. The differential and common mode component $O_{DM}$ and $O_{CM}$ are respectively calculated with eqs. (1) and (2).

$$O_{DM} = \sqrt{|\tilde{A}|^2 + |\tilde{B}|^2 - 2|\tilde{A}||\tilde{B}| \cos(\theta_A - \theta_B)} \frac{|\tilde{A}| \sin \theta_A - |\tilde{B}| \sin \theta_B}{|\tilde{A}| \cos \theta_A - |\tilde{B}| \cos \theta_B} \tag{1}$$

$$O_{CM} = \sqrt{|\tilde{A}|^2 + |\tilde{B}|^2 + 2|\tilde{A}||\tilde{B}| \cos(\theta_A - \theta_B)} \frac{|\tilde{A}| \sin \theta_A + |\tilde{B}| \sin \theta_B}{|\tilde{A}| \cos \theta_A + |\tilde{B}| \cos \theta_B} \tag{2}$$

where $\tilde{A} = |\tilde{A}| e^{j\theta_A} = I_A + jQ_A$, $\tilde{B} = |\tilde{B}| e^{j\theta_B} = I_B + jQ_B$. $I_A$, $Q_A$, $I_B$, $Q_B$ are in-phase and quadrature component of input signal A and B, respectively.

3 Experimental validation

3.1 Experimental setup

Fig. 1(c) and (d) shows experimental setup for mode decomposition of conducted noise voltage with CMDM switch and synchronous measurement of VSA.
tively. A and B represents line length to connect output of LISN (Solar type 9867-5-TS-50-N/Solar electronics company) and CMDM switch or VSA. Measurement result of LISN impedance and $S_{11}$ is shown in Fig. 1(e). Arbitrary waveform generator (AWG33600 A/Keysight/2ch) simulates differential and common mode conduction emission voltage.

### 3.2 Mode decomposition

#### 3.2.1 CMDM switch

Figs. 2 shows the decomposition results for a measured conducted noise voltage with LISN for 1 Vpp sinusoidal input (111 dBµV) from 150 kHz to 30 MHz. Where the length of the signal line A and B are same. Decomposed CM and DM output of the CMDM switch for the common mode input signal is given as the green and the yellow square point in Fig. 2(a), respectively. Due to attenuation characteristic of LISN, input signal is attenuated below a few MHz. Fig. 2(b) shows the compensation result in attenuation characteristic of LISN. Because of the compensation, CM output signal of CMDM switch correspond to the input signals shows amenable frequency characteristic, which keeps 2 Vpp (117 dBµV) in the range of 150 kHz–30 MHz. CMDM gives more than 32 dB mode rejection ratio. Figs. 2(c) and (d) shows the CM and DM output with/without the compensation for the differential mode signal input, respectively. CMDM switch has rejection ratio of 32 dB or more. This result coincide with transmission characteristic of CMDM switch shown in Figs. 1(a) and (b).

![Mode decomposition result for sinusoidal input](image-url)

#### 3.2.2 Inter-VSA phase delay compensation

There are time and phase delay between measurement results of synchronously operated two VSAs, which stem from the individual difference in the measurement setup and apparatus. The frequency characteristic of phase difference between detected vector for synchronously operated two VSA is shown as green line in
Fig. 1(f). The phase difference between two VSA is approximated as a linear function in eq. (3).

$$\theta = R \times f + \theta_0 \text{ [deg]}$$  
(3)

Where $f$ [MHz] is the frequency. $R$ means time delay, which describe as $R = -1.38$ [deg/MHz] and $\theta_0 = -10.4$ is obtained by the least square method, respectively. $R$ corresponds with the difference of cable length 0.76 m. Compensated phase characteristic with eq. (3) is shown in the condition (ii) in Fig. 1(f).

**Mode decomposition with VSA**

The mode decomposition result for the output of synchronously operated two VSAs are shown in Figs. 2. Red and the blue round point gives the calculated common and differential mode for common mode input signal, respectively. The calculated components corresponding to the input signals shows amenable frequency characteristic which are compatible to the result obtained with the CMDM switch.

### 3.3 Comparative study for non-sinusoidal input signal

This section discusses the performance of proposing mode decomposition for non-sinusoidal input signal. Fig. 3(a) shows the voltage on line A and B, whose frequency spectrum is shown in Fig. 3(b). The signal voltage is synthesised of CM and DM in eq. (6) and (7) with eq. (4) and (5).

$$\tilde{A} = \tilde{C}M + \tilde{D}M$$
(4)

$$\tilde{B} = \tilde{C}M - \tilde{D}M$$
(5)

$$\tilde{C}M = 0.5(0.1 \sin 16f't + 0.2 \sin 17f't + 0.3 \sin 18f't + 0.4 \sin 19f't \nonumber
+ 0.5 \sin 20f't + 0.4 \sin 21f't + 0.3 \sin 22f't + 0.2 \sin 23f't \nonumber
+ 0.1 \sin 24f't)$$
(6)

$$\tilde{D}M = \begin{cases} 25 \times 10^6t & (0 \leq t \leq 20 \text{ ns}) \\ 0.5 & (20 \text{ ns} \leq t \leq 250 \text{ ns}) \\ -25 \times 10^6t & (250 \text{ ns} \leq t \leq 270 \text{ ns}) \\ 0 & (270 \text{ ns} \leq t \leq 500 \text{ ns}) \end{cases}$$
(7)

where $f' = 1$ [MHz]. Fig. 3(c) shows the sum and difference signals of A and B. The common mode component are the sum of sinusoidal waveform between 16–24 MHz, the differential mode component are trapezoidal waveform to emulate conducted noise in power electronics circuit. The results of mode decomposition are shown in Fig. 3(d)(e). Calculation result of VSAs correspond with CMDM decomposition result in Fig. 3(d)(e). The voltage amplitude of CM component at 20 MHz are 106.9 dBµV (0.22 V), which has slightly differ from eq. (6). The error cause from spectrum leakage of FFT in VSA. The knee frequency of trapezoidal signal DM spectrum are decided according to pulse width and rise time. Both method were able to obtain appropriate spectrum.
4 Conclusion

This paper studied a mode decomposition of conduction emission voltage with synchronous measurement of two vector signal analyzers. We experimentally compared and evaluated the mode decomposition performance of proposed method using vector calculation of synchronously measured VSA with conventional CMDM switch. We showed that the proposed method has compatible decomposition performance with the conventional CMDM switch, but it can simultaneously obtain CM and DM. Experimental results clarified the possibility of decomposition method based on vector calculation.

Acknowledgments

This work has been implemented under Cross-ministerial Strategic Innovation Promotion Program (SIP Program).