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A Fast Equivalent Method for Modeling Electromagnetic Pulse Response of Cable Bundle Terminated in Arbitrary Loads

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Abstract—An effective fast equivalent cable bundle modeling method is proposed in this paper to study electromagnetic pulse response of complex cable bundle. Compared with traditional equivalent cable bundle method (ECBM), the complete cable bundle is equivalent to only one cable by modification of cable grouping method, which leads to reduction in number of cables and computation progress. The proposed method can perform well not only in pure resistance case, but also in frequency dependent load case by weighted average method (WAM). The computation time and memory acquirement for complete cable bundle model terminated in arbitrary loads have been further reduced by fast equivalent method compared to ECBM, and calculation precision is maintained to meet fast application need. Numerical simulation of coupled currents in observed cable located at a certain distance away from cable bundle by CST software is given to verify accuracy of the method under illumination of high altitude electromagnetic pulse (HEMP).

1. INTRODUCTION

With quick development of modern technology, electronic equipments are becoming more and more sensitive and vulnerable to threats from high altitude electromagnetic pulse (HEMP) [1–4]. HEMP is characterized by short duration, high energy, wide range coverage, and intense electric field strength, which can cause great damage for military and civil electronic equipment and electrical systems [2, 3]. Cable and cable bundle network take an important role in communication among various platforms and systems, which are also primary approaches to couple undesired interference signal [5]. Therefore, it is necessary to study electromagnetic pulse response of cable bundle under HEMP irradiation.

The ability to generate a realistic model of an entire car including all metallic parts and complete cable harnesses is still a strategic challenge in automotive industry [6, 7]. Equivalent cable bundle method (ECBM) [6–8] is an effective method of modeling complex cable bundle to reduce computation time and memory, which is widely accepted in EM immunity [6], emission [7] and crosstalk [9–11] of complex cable bundles over a large frequency range. However, cable grouping method leads to a limit that original ECBM can only be applied to frequency independent loads case, which greatly narrows application of the ECBM. A generalized equivalent cable bundle method (GECBM) is proposed in [12, 13] to calculate cable bundle terminated with arbitrary loads by weighted average method (WAM) in frequency domain. Both ECBM and GECBM sort all the conductors of complete cable bundle into four groups by comparing the modulus of the termination loads to the common mode characteristic impedance.

Although the rigorous application of the ECBM based on four-group decomposition could ensure accurate results, it seems difficult to apply it in high complexity cable problems [14]. In fact, the complexity of cable bundle can be further simplified at the expense of slight loss of accuracy for some special cases. The work by Andrieu et al. show that the behavior of cable bundle with large number

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of cables terminated with pure resistance can be roughly represented by one equivalent cable short-circuited at both ends under illumination of high frequency plane wave, with acceptable error compared to ECBM [14]. In this paper, we study the EM effect of cable bundle under the illumination of HEMP. Considering coupled currents of the observed cable separated at a certain distance away from cable bundle, we can simplify the cable bundle into only one cable.

Our method is based on the assumption that the common mode response is more critical than the differential mode response, as all ECBMs do. The novel cable method combined with WAM can simplify conductors terminated with arbitrary loads, to meet the fast calculation need of realistic applications. Numerical simulation by CST Cable Studio using multi-conductor transmission line network (MTLN) algorithm is performed to obtain strong electromagnetic response of observed cable in different equivalent cases, which verifies effectiveness of the proposed fast equivalent method.

Content in this paper is organized as follows. Section 2 introduces theory of the proposed method. Some obtained simulation results and analysis are presented in Section 3. Section 4 describes concluding remarks.

2. FAST EQUIVALENT METHOD

2.1. Theoretical analysis

The original complete cable bundle terminated with arbitrary loads is presented in Fig. 1. Considering electromagnetic response coupled in cable bundle, the effect of complete conductors can be equivalent to only one cable, just as shown in Fig. 2.

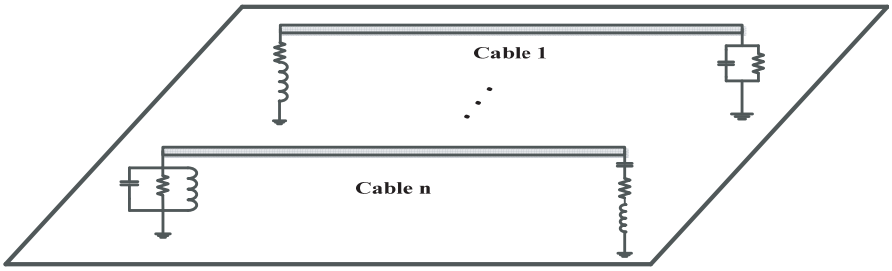

Figure 1. A cable bundle model with cables terminated in arbitrary loads.

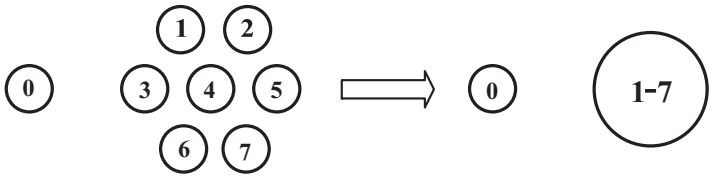

Figure 2. Model of fast equivalent method.

The common forms of MTLN equations on case of N-conductor cable bundle are written as [15]:

$$\frac{\mathrm{d}V(x)}{dx} + Z'I(x) = 0 \tag{1}$$

$$\frac{\mathrm{d}I(x)}{dx} + Y'V(x) = 0 \tag{2}$$

$$Z' = R + jwL' \tag{3}$$

$$Y' = G + jwC' \tag{4}$$

While considering lossless cable in this paper, $R = G = 0$.
Our fast equivalent method is based on the following assumptions:

1) All conductors have the same electric potential, which is also the same as equivalent cable

$$V_{eq} = V_1 = V_2 = \ldots = V_n \tag{5}$$

2) Current of the equivalent cable is the sum of the currents induced on each conductor

$$I_{eq} = I_1 + I_2 + \ldots + I_n \tag{6}$$

The fast method is to model the cable bundle into one equivalent cable, then:

$$\frac{d\mathbf{V_{eq}}}{dz} = -jwL_{eq}\mathbf{I_{eq}} \tag{7}$$

According to Eq. (1), the MTLN equations can be rewritten as:

$$\begin{bmatrix} \frac{dV_1}{dz} \\ \frac{dV_2}{dz} \\ \vdots \\ \frac{dV_n}{dz} \end{bmatrix} = -jw \begin{bmatrix} L_{11} & L_{12} & \ldots & L_{1n} \\ L_{21} & L_{22} & \ldots & L_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & \ldots & L_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \tag{8}$$

Combining Eqs. (5), (6) and (7), we can get

$$\mathbf{I_{eq}} = \sum_{i=0}^{n}\sum_{j=0}^{n}\mathbf{A}_{ij}\frac{d\mathbf{V_{eq}}}{dz} \tag{9}$$

$$L_{eq} = -\frac{1}{jw\sum\limits_{i=0}^{n}\sum\limits_{j=0}^{n}A_{ij}} \tag{10}$$

where

$$[A] = \frac{1}{jw}\begin{bmatrix} L_{11} & L_{12} & \ldots & L_{1n} \\ L_{21} & L_{22} & \ldots & L_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & \ldots & L_{nn} \end{bmatrix}^{-1} \tag{11}$$

and A_{ij} indicates element in matrix $\mathbf{A}$.

2.2. Related Parameters

To model the equivalent cable, some basic parameters containing position, height above the ground and radius should be figured out.

2.2.1. Position of Equivalent Cable

Supposing that center position of each original cable is (x_i, y_i), the equivalent cable position is (X, Y), then X, Y correspond to the average of positions of all conductors.

$$X = \frac{\sum\limits_{i=1}^{N}x_i}{N} \tag{12}$$

$$Y = \frac{\sum\limits_{i=1}^{N}y_i}{N} \tag{13}$$

2.2.2. Height above the Ground

Equivalent height of equivalent conductor h_{eq} is figured out by the average value of heights of all the conductors.

$$h_{eq} = \frac{\sum_{i=1}^{N} h_i}{N} \tag{14}$$

2.2.3. Radius of Equivalent Cable

Original formula of inductance is

$$L = \frac{\mu_0}{2\pi} \ln \frac{2h}{r} \tag{15}$$

Combined with (10), then final formula of equivalent cable radius is obtained:

$$r_{eq} = \frac{2h_{eq}}{\exp\left(\frac{2\pi L_{eq}}{\mu_0}\right)} \tag{16}$$

2.3. Termination Loads of Equivalent Cable

Termination load impedances consist of resistance R, inductance L, capacitance C and their arbitrary hybrid connections at both ends of cables. In this paper, pure resistance and hybrid case are considered. Based on Eqs. (5) and (6), equivalent cable loads are obtained by putting all the impedance loads connected in parallel, just as the method in [6].

$$Z_{eq} = Z_1 \| Z_2 \| \ldots \| Z_n \tag{17}$$

2.3.1. Pure Resistance

On case of pure resistance, termination load impedance of equivalent cable is a value of all the conductors connected in parallel.

$$Z_{eq} = R_1 \| R_2 \| \ldots \| R_n = \frac{1}{\frac{1}{R_1} + \ldots + \frac{1}{R_n}} \tag{18}$$

2.3.2. Hybrid Case

Hybrid case contains resistance, inductance, capacitance and their arbitrary connections. Applying GECBM in [12], frequency dependent loads are transformed into resistances by WAM. The weighted average value (WAV) of all the termination load impedances is calculated by considering excitation signal and termination load impedance's different frequency components at the same time [12].

$$\underset{1(2)j}{\dot{Z}} = \frac{\sum_{i=0}^{M} \left(a_i \left| Z_{1(2)ji} \right|\right)}{\sum_{i=0}^{M} a_i} \tag{19}$$

where $Z_{1(2)ji}$ and a_i denote each end load impedance of the jth cable and amplitude of the excitation signal at sampling frequency f_i $(i = 0, \ldots, m;\ j = 1, \ldots, n)$. m is the total frequency sampling number in $[0, f_{\max}]$, and n is the total cable number in the complete cable bundle.

Following theory of WAV of all termination load impedances, we can get equivalent termination load impedances independent of frequency from original frequency dependent case. Then the situation turns into pure resistance case, and the equivalent termination loads can be calculated by Eq. (17).

3. SIMULATION ANALYSIS

All the simulation results in this paper are obtained by CST Cable Studio using MTLN algorithm.

3.1. Excitation Source

Electric field intensity waveform of HEMP in time domain is a double-exponential pulse, as shown in Fig. 3. Fig. 4 reveals frequency spectrum of HEMP.

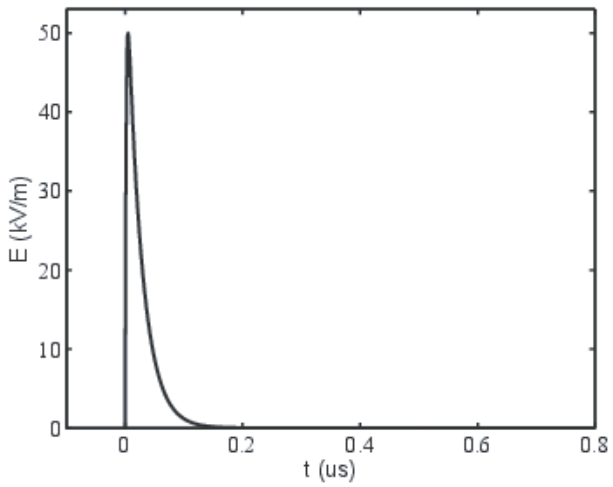

Figure 3. Waveform of HEMP.

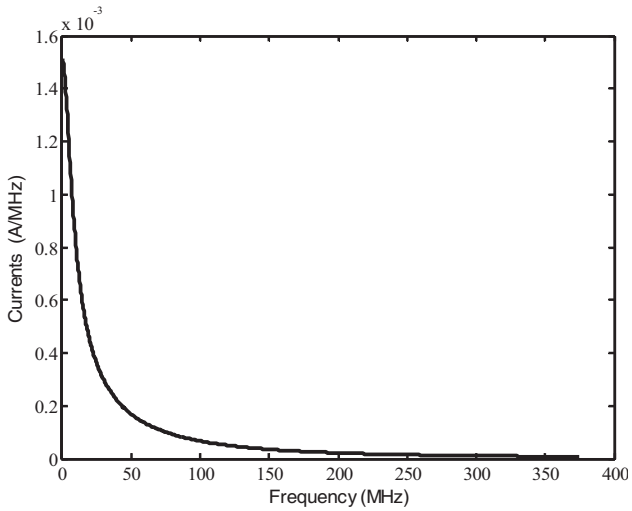

Figure 4. Frequency spectrum of HEMP.

3.2. Case of Pure Resistance

There are seven conductors (cables 1–7) to be simplified and one observed conductor (cable 0) to be monitored just as shown in Fig. 5, and termination loads of complete conductors are presented in Table 1.

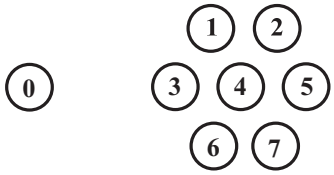

Figure 5. Complete cable bundle.

Table 1. The termination loads of complete conductors (unit: Ω).

Conductor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**
End 1	50	100	10 k	1 k	500	150 k	1 M	50
End 2	50	10	150	20 M	500	20	15 k	50

The complete cable settings are: cables 1–7 are bare wire with radius of 0.5 mm, and the heights of cables are 21.73 mm, 21.73 mm, 20 mm, 20 mm, 20 mm, 18.27 mm, 18.27 mm, respectively. Interval of two adjacent conductors is 2 mm. The distance between cable 0 and center of cable bundle is 20 mm.

Then complete matrixes of inductance and capacitance of original cable bundle settings are figured out as Eqs. (20) and (21).

$$L = \begin{bmatrix} 893 & 616 & 607.7 & 607.7 & 498.3 & 489.3 & 460.8 \\ 616 & 893 & 498.3 & 607.7 & 607.7 & 460.8 & 489.3 \\ 607.7 & 498.3 & 876.4 & 599.4 & 461.5 & 590.4 & 481.1 \\ 607.7 & 607.7 & 599.4 & 876.4 & 599.4 & 590.4 & 590.4 \\ 498.3 & 607.7 & 461.5 & 599.4 & 876.4 & 481.1 & 590.4 \\ 489.3 & 460.8 & 590.4 & 590.4 & 481.1 & 858.3 & 581.4 \\ 460.8 & 489.3 & 481.1 & 590.4 & 590.4 & 581.4 & 858.3 \end{bmatrix} \text{nH/m} \tag{20}$$

$$C = \begin{bmatrix} 33.06 & -11.71 & -11.66 & -7.18 & 0.16 & 0.21 & 0.15 \\ -11.71 & 33.06 & 0.16 & -7.18 & -11.66 & 0.15 & 0.21 \\ -11.66 & 0.16 & 33.16 & -7.19 & 0.15 & -11.55 & 0.26 \\ -7.18 & -7.18 & -7.19 & 42.18 & -7.19 & -7.21 & -7.21 \\ 0.16 & -11.67 & 0.15 & -7.19 & 33.16 & 0.26 & -11.55 \\ 0.21 & 0.15 & -11.55 & -7.21 & 0.26 & 33.29 & -11.49 \\ 0.15 & 0.21 & 0.26 & -7.21 & -11.55 & -11.49 & 33.29 \end{bmatrix} \text{pF/m} \tag{21}$$

Then, we use ECBM and fast equivalent method to calculate electromagnetic response under HEMP irradiation, respectively.

3.2.1. Original ECBM

By original ECBM in [6, 7], the calculated cable bundle common mode characteristic impedance $Z_{mc} = 175.31\,\Omega$. Then cable decomposition is described as:

Group 1: conductors 1, 2; Group 2: conductors 3, 6; Group 3: conductors 4, 5, 7.

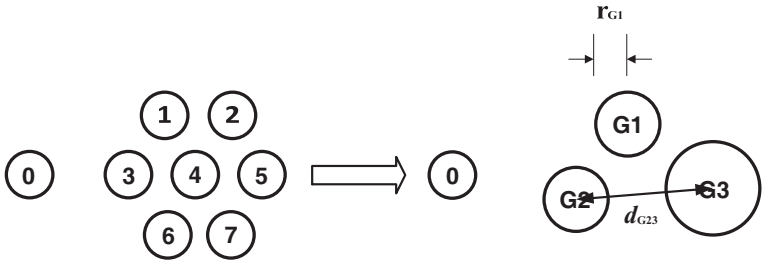

Figure 6. Reduced cable bundle by ECBM.

The model of equivalent cable bundle by ECBM is presented in Fig. 6. Then, according to the theory of ECBM, reduced inductance matrix is as:

$$L_{eq} = \begin{bmatrix} 754.5 & 514 & 545.2 \\ 514 & 728.9 & 532.5 \\ 545.2 & 532.5 & 685.7 \end{bmatrix} \text{nH/m} \tag{22}$$

The adjusted cross-section geometry parameters are described in Table 2, and equivalent termination loads are presented in Table 3.

3.2.2. Fast Equivalent Method

Following the fast equivalent algorithm introduced in Section 2, the parameters are calculated. Equivalent cable position is the same as cable 4 because of symmetry of the complete cable bundle settings. According to complete matrix of inductance in Eq. (20) as well as formulas of inductance Eqs. (10) and (15), reduced inductance of equivalent cable $L_{eq} = 584.37\,\text{nH}$. By Eq. (16), equivalent radius $r_{eq} = 2.15\,\text{mm}$. Termination loads of equivalent cable are figured as: End 1 is $30.20\,\Omega$, and End 2 is $5.59\,\Omega$.

Table 2. Cross section geometry parameters (unit: mm).

Parameters	G1	G2	G3
Radius	1.0	1.0	1.25
Height	22.0	19.1	19.7
Interval	$d12 = 3.15$	$d13 = 2.7$	$d23 = 2.71$

FOOTNOTE: dij indicates the interval distance between ith conductor and jth conductor.

Table 3. Reduced termination loads (unit: Ω).

Conductor	G1	G2	G3
End 1	33.33	9376.0	333.22
End 2	8.33	17.65	483.86

3.2.3. Comparison of Two Methods

Simulation settings: an infinite metal ground, observed cable 0 is a single conductor of LIFY_0qmm10, and incident direction of excitation source is normal to the cable bundle. The observed cable responses of complete case, reduced by ECBM and fast equivalent method at both cable ends, are presented in Fig. 7.

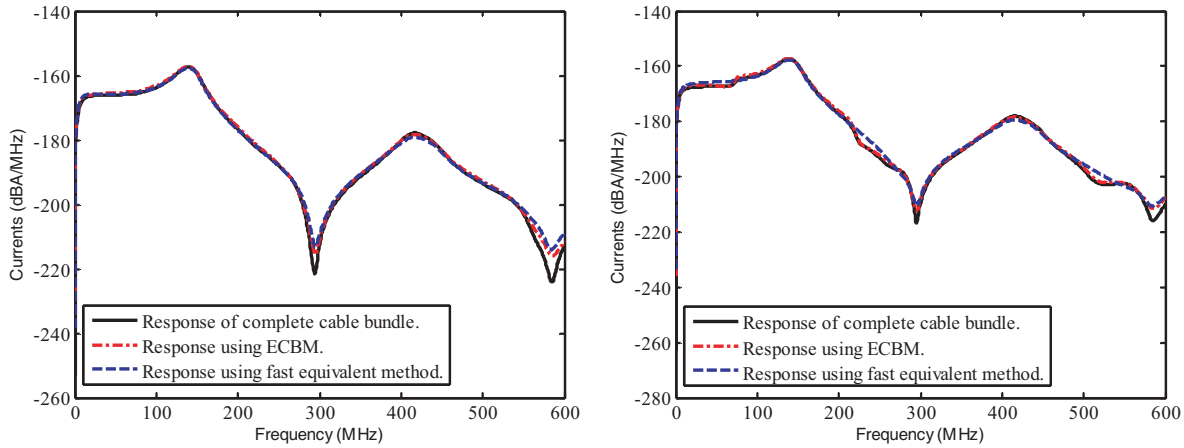

Figure 7. Response of observed cable 0 on pure resistance case. (a) End 1. (b) End 2.

As shown in Fig. 7, the response of the proposed method has a little deviation especially at high frequency resonance points. However, the whole trends of three current curves are the same, with good agreement. The statistic results of computation time and memory requirement are displayed in Table 4.

Table 4. Comparison of computation time and memory requirement.

Case of conductors	Computation time	Acquired memory
The complete cable	2 min 34 sec	60616 kB
ECBM	1 min 20 sec	50916 kB
Fast equivalent method	50 sec	45588 kB

From Table 4, we can observe that computation time of fast equivalent method is reduced by 67.5% and memory requirement reduced by 24.8%, compared with the complete cable, while compared to ECBM, computation time is reduced by 37.5% and memory requirement reduced by 10.4%, which verifies the effectiveness of proposed method.

3.3. Case of Hybrid Loads

In hybrid loads case, the original ECBM is not appropriate anymore. Here, we apply GECBM and our fast equivalent method, respectively, and compare with the response of complete cable bundle. The complete cable bundle model is the same as Fig. 5.

The upper cutoff frequency of HEMP is chosen as 300 MHz, total frequency sampling number as 1201, and interval of frequency sampling as 0.25 MHz. Original termination loads and WAV of all termination load impedances are displayed as shown in Table 5.

Table 5. WAV of all termination load impedances.

Conductor	**0**	**1**	**2**	**3**
$\mathbf{Z}_1$	$50\,\Omega$	$50\,\Omega$	$100\,\Omega + 0.1\,\mu\text{H}$	$10\,\text{k}\Omega \| 100\,\text{pF}$
$\|Z_1\|$	$50\,\Omega$	$50\,\Omega$	$109\,\Omega$	$379\,\Omega$
$\mathbf{Z}_2$	$50\,\Omega$	$10\,\text{k}\Omega$	$100\,\Omega \| 10\,\text{pF}$	$0.1\,\Omega + 40\,\text{nH} + 200\,\text{pF}$
$\|Z_2\|$	$50\,\Omega$	$10\,\text{k}\Omega$	$22.6\,\Omega$	$147\,\Omega$
Conductor	**4**	**5**	**6**	**7**
$\mathbf{Z}_1$	$0.2\,\Omega + 20\,\text{nH} + 100\,\text{pF}$	$15\,\text{k}\Omega \| 40\,\text{nH} \| 20\,\text{pF}$	$150\,\text{k}\Omega + 1\,\mu\text{H}$	$1\,\text{M}\Omega$
$\|Z_1\|$	$289\,\Omega$	$44\,\Omega$	$150\,\text{k}\Omega$	$1\,\text{M}\Omega$
$\mathbf{Z}_2$	$20\,\text{k}\Omega \| 200\,\text{nH} \| 10\,\text{pF}$	$500\,\Omega + 400\,\text{nH}$	$750\,\Omega \| 50\,\text{pF}$	$800\,\Omega + 600\,\text{nH}$
$\|Z_2\|$	$164\,\Omega$	$530.8\,\Omega$	$45.6\,\Omega$	$844\,\Omega$

3.3.1. GECBM

Following GECBM, common mode impedance is as $Z_{mc} = 177\,\Omega$. Considering modulus of the terminal loads at each end of the cable, the cable groups are:

Group 1: 2; Group 2: 7; Group 3: 1, 5; Group 4: 3, 4, 6.

The reduced model of cable bundle by GECBM is shown in Fig. 8. Cross-section geometry parameters and reduced termination loads are shown in Table 6 and Table 7, respectively.

Table 6. Cross-section geometry parameters (unit: mm).

Parameters	**G1**	**G2**	**G3**	**G4**
Radius	0.50	0.50	1.31	1.26
Height	22.00	18.00	2.00	19.50
Interval	$d12 = 4.00$	$d13 = 2.00$	$d14 = 3.61$	$d23 = 2.46$
	$d24 = 3.00$		$d34 = 1.73$	

FOOTNOTE: dij indicates the interval distance between ith conductor and jth conductor.

3.3.2. Fast Equivalent Method

By weighted average method described in Subsection 2.3, equivalent termination loads are calculated: End 1 is $17.2\,\Omega$, and End 2 is $12.2\,\Omega$. Following the same simulation setting and procedure as the pure resistance case in Subsection 3.2, the responses of complete and equivalent cable bundles are obtained as Fig. 9.

Table 7. Reduced termination loads (unit: Ω).

Conductor	G1	G2	G3	G4
End 1	109	1 M	23.4	163.8
End 2	22.6	844.0	504.0	28.7

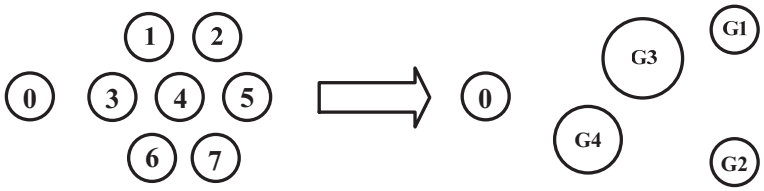

Figure 8. Reduced cable bundle by GECBM.

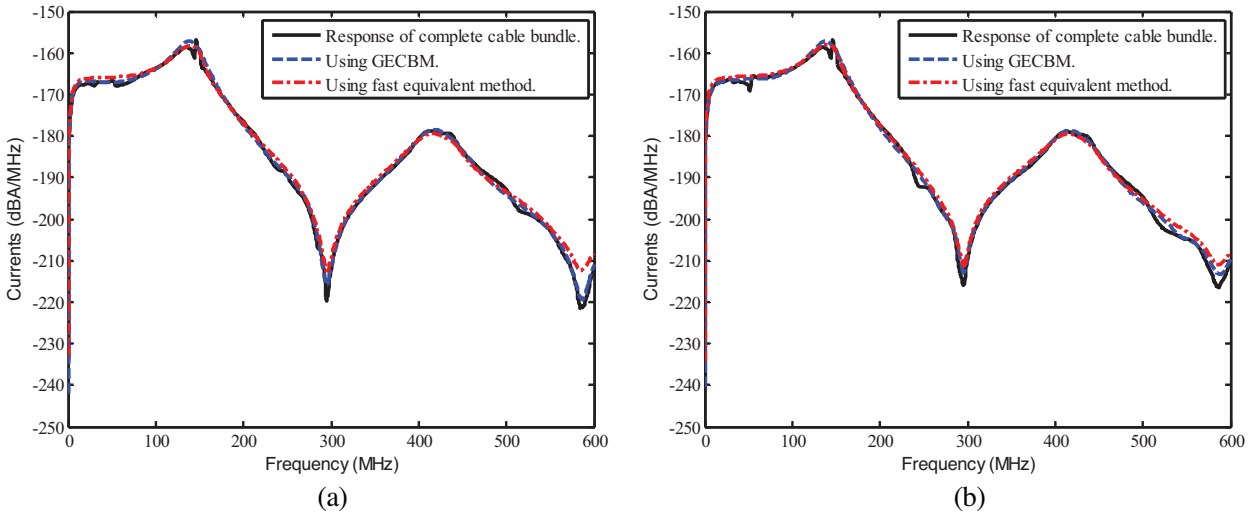

Figure 9. Response of observed cable 0 on hybrid load case. (a) End 1. (b) End 2.

It can be seen that GECBM results have excellent precision, while fast equivalent method combined with WAM also has good agreement generally, other than a little deviation at high frequency resonance points. The statistics results of computation time and memory requirement are displayed in Table 8.

Table 8. Comparison of computation time and memory requirement.

Case of conductors	Computation time	Acquired memory
The complete cable	3 min 53 sec	56912 kB
GECBM	2 min 20 sec	54408 kB
Fast equivalent method	1 min 19 sec	47056 kB

In terms of computation time and memory requirement, compared with the complete cable, computation time of fast equivalent method combined with WAV is reduced by 66.1% and memory requirement reduced by 17.3%, while compared to GECBM, computation time is reduced by 43.6% and memory requirement reduced by 13.5%.

In summary, the results of fast equivalent method have generally good agreement with ECBM and

GECBM, in spite of slight loss of calculation accuracy at high frequency resonance points. However, coupled energy in cable 0 at high frequency is much smaller than that of other frequency components due to HEMP energy distribution as shown in Fig. 4. Therefore, the discrepancy in high frequency will not have great impact on overall results. Moreover, the proposed equivalent method is easier to perform, and calculation time and memory is significantly reduced to meet fast engineering application need.

3.4. Influence of Distance between Observed Cable and Cable Bundle

Finally, the influence of distance between cable 0 and cable bundle is studied to further verify the effectiveness of the fast equivalent method. Here, we define **d** as the distance between cable 0 and the center of cable bundle, as shown in Fig. 10. Both cases of terminated loads are analyzed in detail.

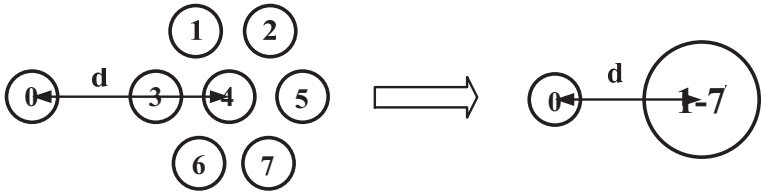

Figure 10. The distance between cable 0 and cable bundle.

3.4.1. Case of Pure Resistance

In part of Subsections 3.2 and 3.3, the distance **d** equals 20 mm. Then, we change **d** from 20 mm to 6 mm with step of 2 mm. In particular, **d** equaling 6 mm means that the interval of cable 0 and cable 3 is 2 mm, which means that cable 0 is almost a part of the cable bundle. The simulation results are shown as follows, and only part of the results with several distances **d** are presented for limit of content.

From Fig. 11 to Fig. 13 and together with Fig. 7, we can see that the trends of three curves are always same. However, accuracy of the proposed method is proportional to **d**. As **d** decreases, the result of fast method tends to smooth the resonance part of the complete cable bundle curve. Since the fast method is an approximation method at the expense of losing accuracy compared to ECBM,

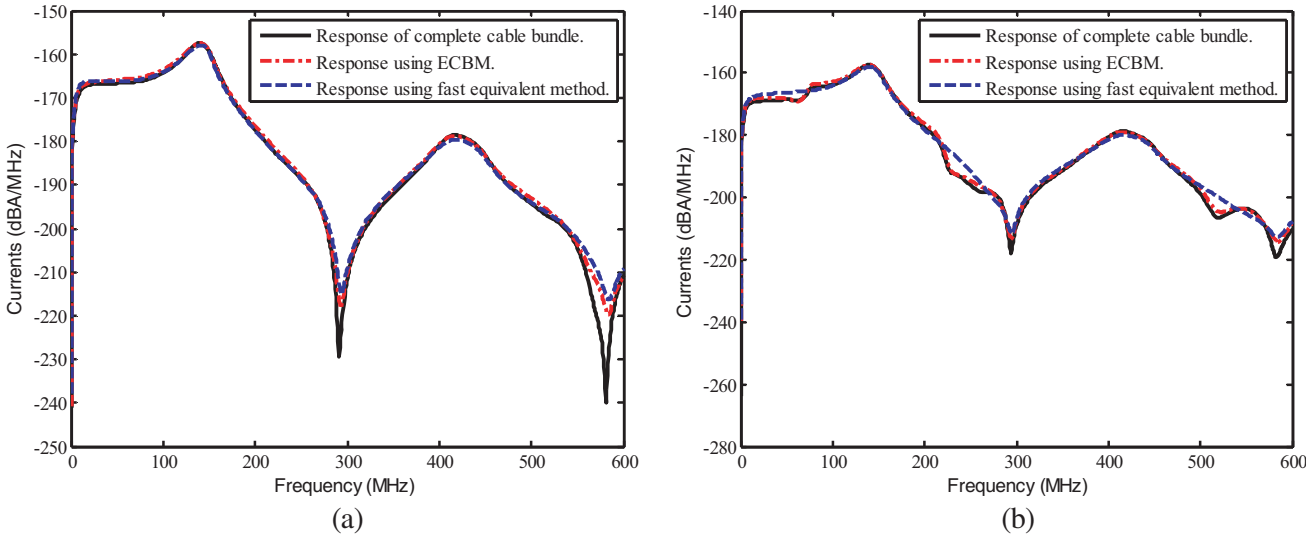

Figure 11. Response of observed cable 0 with $d = 12$ mm. (a) End 1. (b) End 2.

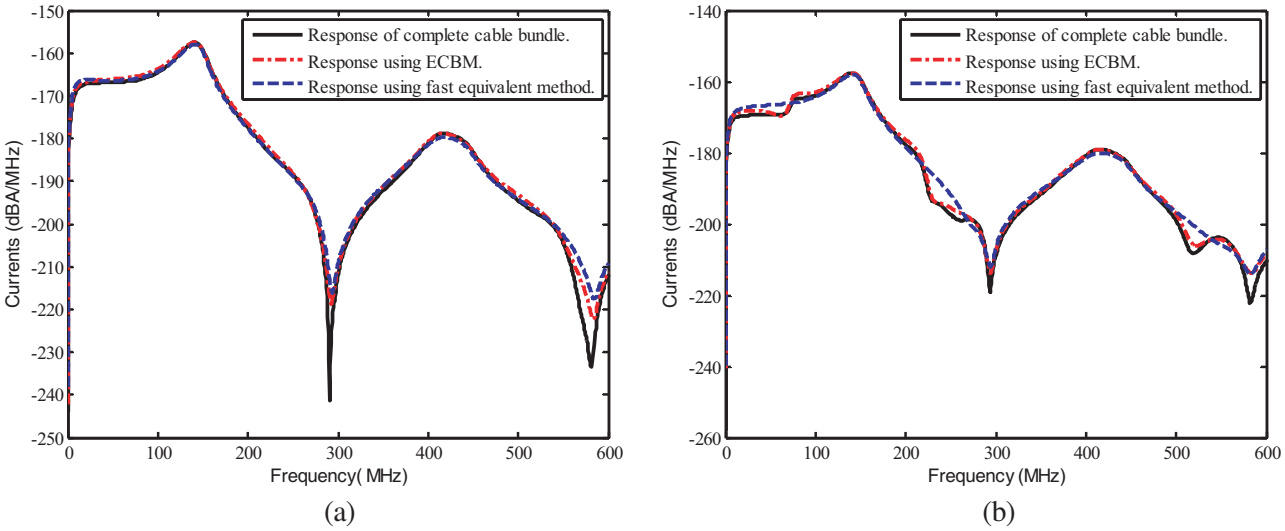

Figure 12. Response of observed cable 0 with $d = 10$ mm. (a) End 1. (b) End 2.

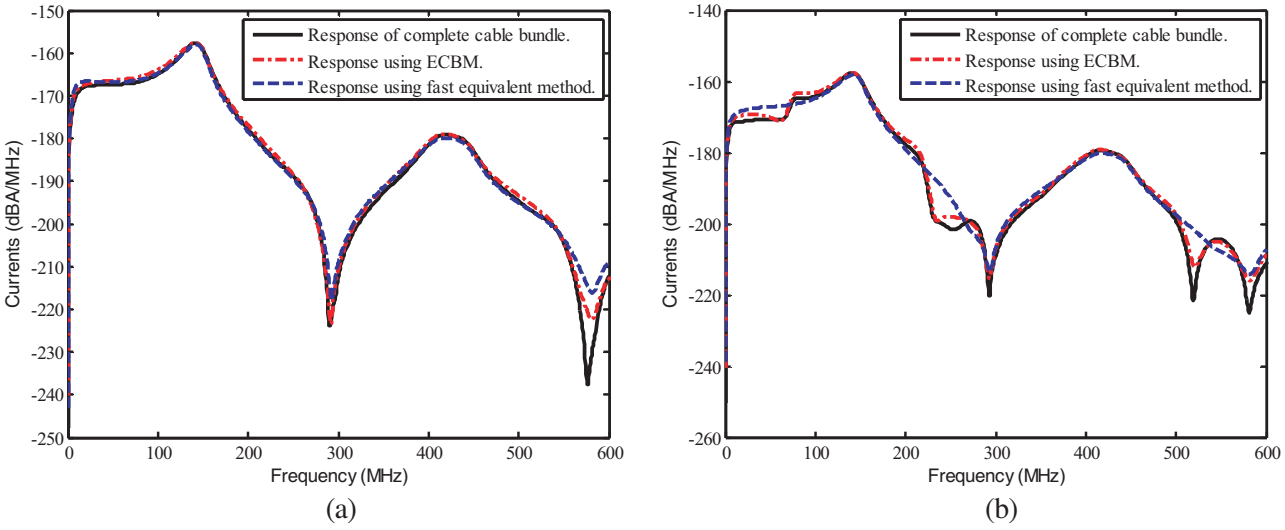

Figure 13. Response of observed cable 0 with $d = 6$ mm. (a) End 1. (b) End 2.

while **d** is smaller, the coupling effect between cable 0 and cable bundle is stronger, and caused error will increase accordingly. If **d** equals 6 mm, the one equivalent cable model cannot sufficiently represent the cable bundle. While **d** is not smaller than 10 mm, the model is effective and can yield satisfactory results. The discrepancy of responses of two termination ends is derived from terminated loads.

3.4.2. Case of Hybrid Loads

Similarly, while cable bundle is terminated with arbitrary loads, the influence of **d** is considered as well.

As shown in Figs. 14–16, as **d** becomes smaller, more resonances will appear in the curve of the complete cable bundle. Both GECBM and fast method tend to smooth these resonance parts of the curve. So both methods will fail as **d** is small enough, for **d** equaling 6 mm as an example. The range of **d** not smaller than 10 mm is an acceptable work scope.

In summary, the proposed fast method is effective on condition that the observed cable 0 is separated at a certain distance from the cable bundle.

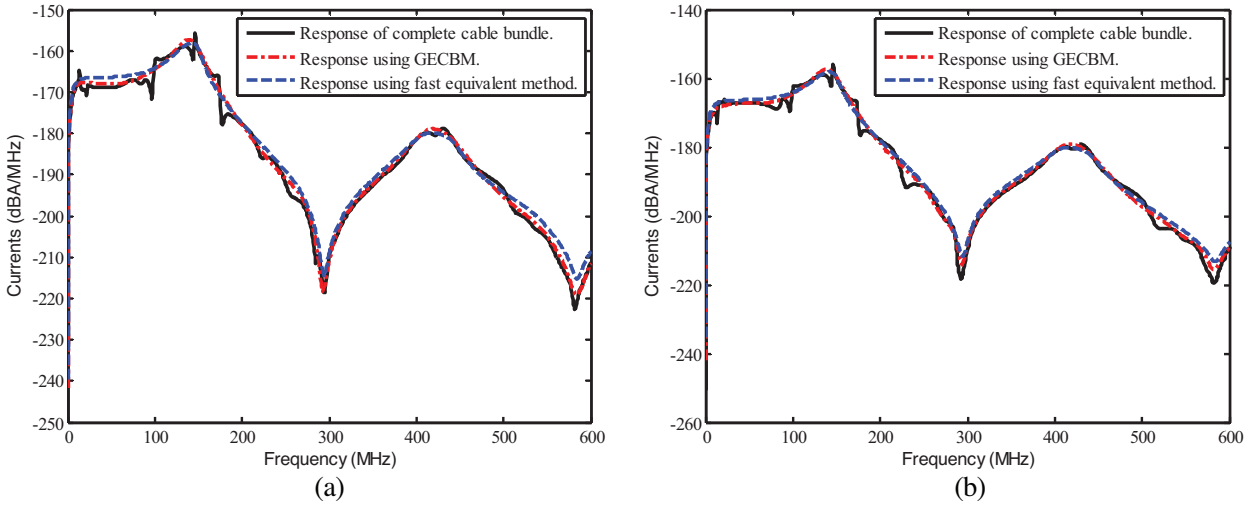

Figure 14. Response of observed cable 0 with $d = 12\,\text{mm}$. (a) End 1. (b) End 2.

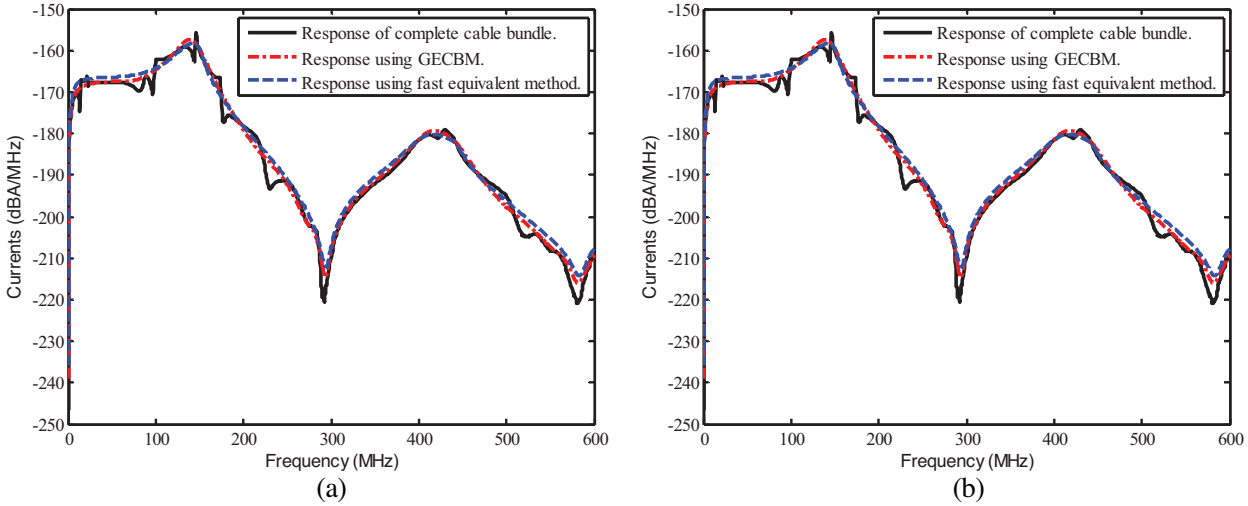

Figure 15. Response of observed cable 0 with $d = 10\,\text{mm}$. (a) End 1. (b) End 2.

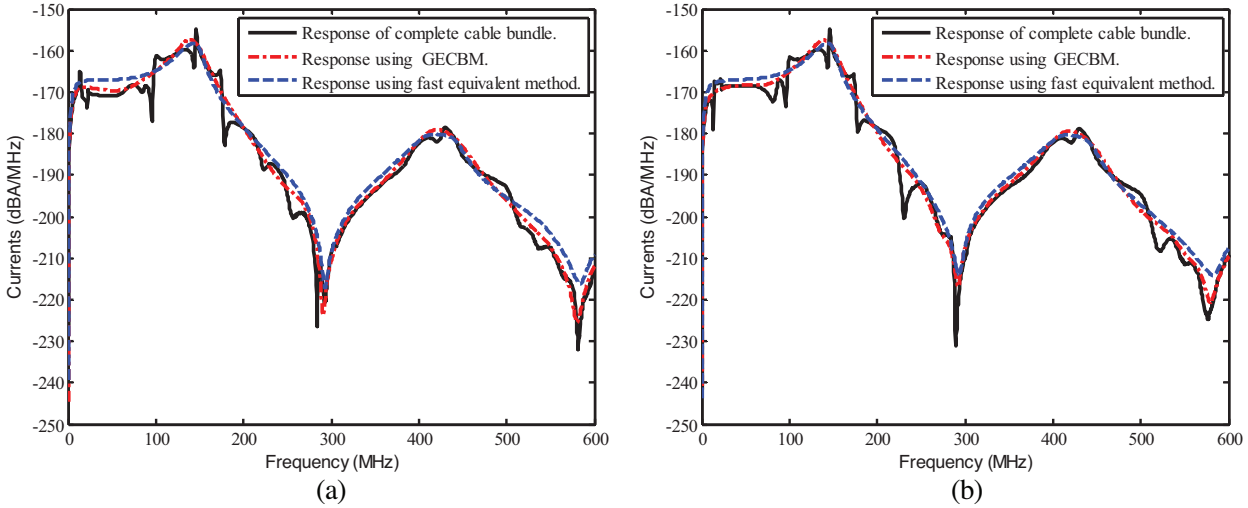

Figure 16. Response of observed cable 0 with $d = 6\,\text{mm}$. (a) End 1. (b) End 2.

4. CONCLUSIONS

This paper proposes a fast equivalent method of cable bundle terminated in arbitrary loads for electromagnetic pulse response modeling. The complex cable bundle can be simplified into only one cable, which can perform well not only in pure resistance case, but in frequency dependent loads case by weighted average method. The computation time and memory of the proposed method are improved with acceptable equivalent precision compared to ECBM. Numerical simulations of cable response of observed cable keeping a certain distance away from cable bundle by CST software are given to validate the efficiency and advantages of the method under illumination of HEMP.

In this paper, the cable electromagnetic response is calculated by MTLN algorithm. When MTLN algorithm is deficient, full wave analysis algorithm is needed to verify the effectiveness of the proposed method. The effectiveness of the method for other applications should be investigated and verified in the future.

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