Investigation on the shading effect of reinforced concrete construction to lightning radiation field based on TDIE method

Shanqiang GU, Di LI, Chun ZHAO, Xiangxue ZENG
State Grid Electric Research Institute
Wuhan Hubei, China

Zhibin ZHAO, Chouwei NI
State Key Laboratory of Alternate Electrical Power System
with Renewable Energy Sources
North China Electric Power University
Changping Beijing, China

Abstract—**Based on the method of moment (MOM) and marching on-in-time method (MOT), a new method to solve the time domain integral equation (TDIE) was put forward, which can be used to investigate the transient response of the complex electrical networks and those with lumped parameters electrical element effectively. With the axial currents on the metal conductors taken as unknown variables, and the piecewise linear function selected as basis function, the time invariant matrix is set up by applying subdomain match method. As the matrix inversion is removed from calculation process, the efficiency is improved significantly. Comparison of the results and those obtained by using the method of multi-conductor transmission lines (MTL) displays little difference. Finally, the proposed method, which is applicable to far field, is used to analyze the effect of a simplified reinforced concrete building on the lightning radiation magnetic field, and some useful results are obtained.**

Keywords- Electromagnetic field; numerical analysis; moment methods Complex thin wire structures; TDIE; Transient electromagnetic response

I. INTRODUCTION

Due to the widely existence of tall reinforced concrete constructions in city, the lightning radiation electromagnetic field detected by nearby lightning location sensor may be influenced significantly. Accordingly the peak value and derivative of the corresponding lightning current derived from the measured lightning radiation magnetic field may deviate from their true values. In order to obtain lightning current reliable enough, it is necessary to investigate the shading effect of the reinforced concrete construction on the lightning radiation magnetic field and specify the minimum distance from the lightning detection system to nearby tall building further.

Usually most literature are concerned with the shielding effect of reinforced concrete construction on the radiation electromagnetic field in space, typically as discussed in [1, 2]. There are two approaches widely used to investigate the shielding effect of the reinforced concrete buildings exactly. The first is based on FDTD or TLM method [1], which is complicated for reinforced concrete despite the relatively simple separation of space. Additionally, it is not convenient to determine the electromagnetic field of any point in space. The second one, using volume cell MoM to investigate the scattering field of concrete block or analogical lump medium [2], is also not applicable to reinforce concrete. For the construction large enough, the solution is difficult due to the too many unknown variables and considerable computation, unless the fast multi-pole or other techniques are introduced. Furthermore, in the research on the shading performance of reinforced concrete construction to electromagnetic field in space, both the influence of steel grid and that of concrete should be taken into account, thus more efficient calculation is required.

In view of the metal grid largely existing in building, this paper is concerned on a rapid direct time domain method applicable for complicated model. Taking the axial current of the conductor as unknown variable, and selecting segment-linear function as base current, a relation matrix independent of time is constructed by using domain-sharing matching method. Because the inverse calculation of the matrix in the marching on-in-time process is removed, the calculation efficiency is improved significantly. Due to the introduction of domain-sharing matching method, the space interval can be increased appropriately. Thereby it needs fewer segments to achieve more satisfactory precision.

Moreover, based on the presented method which is of a direct time-domain method applicable for complicated conductor, early transient response can be analyzed efficiently. The model with lumped source and load taken into account can be improved as well.

Since the inversion of lightning current is mainly dependent on the lightning radiation magnetic field intensity, only the waveform of the radiation magnetic field is displayed. At last, the proposed method is used to analyze the effect of a simplified reinforced concrete building to the lightning radiation magnetic field.

II. DESCRIPTION OF THE APPROACH

In order to reasonably simplify the calculation model of reinforced concrete construction, the following hypotheses are necessary. They are: 1) in view of the specification in architecture, the reinforced grid is not smaller than 15cm×15cm. Thus, compared with the scattering of reinforced grid, the scattering of the concrete is neglected, 2) the radius of the steel conductor buried in the concrete is small enough to be modeled as thin wire, 3) the ground plane is perfect electric conductor. The concerned problem can be simplified to the scattering of metal grid conductor.

A. Time-domain Integral Equation of Thin Conductor

As described in the scattering theory, on the surface of each straight conductor segment, the tangential component of the incidence electric field is equal to that of the scattering electric field, namely

$$\boldsymbol{E}^i_{\ l} = \partial \boldsymbol{A}_l / \partial t + \partial \varphi / \partial l \qquad (1)$$

where

$\boldsymbol{E}^i$—incidence electric field intensity on conductor surface,

$\boldsymbol{A}$—vector potential on conductor surface generated by axial current,

φ—scalar potential on conductor surface generated by line charge,

l—axial direction on conductor surface.

In the infinite free space, there

$$A_l\left(\boldsymbol{r},t\right) = \frac{\mu}{4\pi} \int_{l'} \frac{I(\boldsymbol{r}',t-R/c)}{R} dl' \qquad (2)$$

$$\varphi\left(\boldsymbol{r},t\right) = \frac{1}{4\pi\varepsilon} \int_{l'} \frac{q(\boldsymbol{r}',t-R/c)}{R} dl' \qquad (3)$$

where

μ, ε—permeability and permittivity of the space,

$R = |\boldsymbol{r} - \boldsymbol{r}'|$—distance from field point to source point,

l'—axial coordinate of conductor.

By introducing (2) and (3) into (1), the time-domain integral equation of thin conductor in free space can be obtained.

B. Selection of Basis Function

With the axial current approximately expressed in terms of a group of basic functions, the time-domain integral equation of electric field can be solved by using MoM. Subdomain basis function is selected. The conductor axis is separated into N segments, as shown in Fig. 1. For each segment, applying linear function as base function, that is
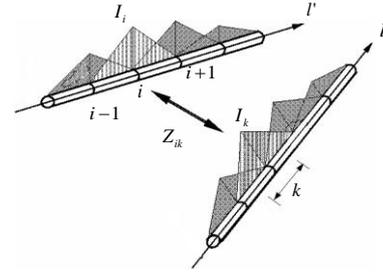

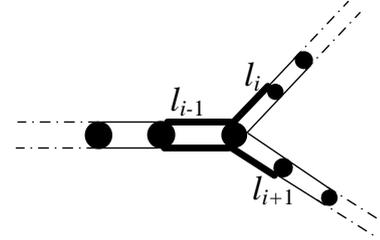Figure 1. Current model of the Wire segments

Figure 2. Location to calculate the scalar and vector potential

For each segment, the roof-top basis function is used to expand the unknown electric current, that is

$$I = \sum_{n=1}^{N} \alpha_n I_n \qquad (4)$$

where α is unknown variables.

C. Selection of Weight Function

Subdomain match method is used to perform weighted mathematic operation. With the midpoint of one conductor segment and the next conductor segment taken as the begin point and end point of the calculation segment of potential function, as shown in fig.1, the weight function is given by

$$\omega_i\left(l\right) = \begin{cases} 1 & l_{i-1} < l < l_i \\ 0 & others \end{cases} \qquad (5)$$

where l_i denotes the midpoint coordinate of each conductor segment. Compared with point match method, the space interval can be increased remarkably so that the segment number decreases and calculation efficiency is improved. Being independent of the conduction position in space, the discussed weight mode is applicable to complicated conductor. For each calculation segment, performing time dispersion by using marching on-in-time method, the weight function is selected as

$$\omega_j\left(t\right) = \delta\left(t - t_j\right) \qquad (6)$$

D. Foundation of Equation

For the sake of better treatment of complicated structure, integral operation is performed on the field point at both sides of (1). For the second term on the right, there

$$\int_l(\partial\varphi/\partial l)dl = \int_l(\partial\varphi/\partial l)dl = \varphi(l_e,t) - \varphi(l_s,t) \quad (7)$$

where, l_s and l_e respectively denote the beginning and end points of each conductor segment. Introducing (4) into the integration of (1), we obtain

$$V^s(t) = \frac{\partial\Phi(t)}{\partial t} + \varphi(l_e,t) - \varphi(l_s,t) \quad (8)$$

where $V^s(t) = \int_l \bar{E}_t^s(l,t)dl$, $\Phi(t) = \int_l A_t(l,t)dl$.

If the conductor is separated into N segments and has M nodes, there will be 2N－M calculation segments. Performing weighted operation on the integral equation of each calculation segment, replacing differential operation with difference operation, then 2N－M linear independent equations can be obtained, they are

$$V_{j,n}^s = \frac{\Phi_{j,n} - \Phi_{j,n-1}}{\Delta t} + \varphi_{j,n} - \varphi_{j-1,n} \quad (9)$$

Substitutes $\psi = \partial\varphi(l,t)/\partial t$, then

$$\varphi_{j,n} = \varphi_{j,n-1} + \psi_{j,n}\Delta t \quad (10)$$

Considering $\partial q/\partial t = -\partial I/\partial l'$, ψ can be expressed as

$$\psi = -\frac{1}{4\pi\varepsilon}\int_{l'}\frac{1}{R}\cdot\frac{\partial}{\partial l'}I(l,l',t-R/c)dl' \quad (11)$$

Thus (5) is rebuilt and only the unknown coefficient α is taken as unknown variable.

E. Solution of Equations

Introducing (10) into (9) and rearranging, can obtain

$$\begin{aligned}
&\Phi_{j,n} + \psi_{j,n}\Delta t^2 - \psi_{j-1,n}\Delta t^2 \\
&= V_{j,n}\Delta t + \Phi_{j,n-1} + (\varphi_{j,n-1} - \varphi_{j-1,n-1})\Delta t
\end{aligned} \quad (12)$$

The left side is composed of the current dynamic vector potential and dynamic scalar potential. Except for the given incidence field, the rest on the right side comprises the dynamic vector potential and dynamic scalar potential of the preceding time. Where $V_{j,n}$ is known and relates to the incidence electric field intensity at current time, $\varphi_{j,n-1}$、$\varphi_{j-1,n-1}$ is the dynamic scalar potential resulted from the calculation at preceding time. Φ and ψ can be determined from above calculation, which can be expressed in terms of the instant current and the current of each previous time.

The coefficient matrix on the left side of (12) contains only the contribution of the axial current at the conductor segment which is of zero time delay with the calculation segment on the conductor surface. For the conductor segment of nonzero time delay, the contribution of its axial current segment is embodied in the column vector to the right of the matrix.

With the undetermined coefficient α_n of the instant current at each surface element as unknown variable, the resultant equation can be written as

$$[K][A] = [B] \quad (13)$$

The elements of K are determined through double integration. It is need to note that, the double integration is independent of time and has nothing to do with the time step and marching on-in-time process. Only once double integration in the solution will not increase the calculation obviously.

The unknown coefficients α of the N segments can be obtained from (13). Note that matrix K is independent of time, constitution and inversion of which need to be performed only once in the whole solution.

The scattering field of surface element in free space can be obtained by using above method. Since the effect of the ground on the conductor above it can be considered by introducing equivalent image conductor, with the ground taken as perfect conductor. The proposed method can be applied to investigating the scattering field of metal surface above perfect conductive ground.

III. VALIDATION

To validate the proposed method, the above method and the multi-conductor-transmission line method given in literature [8] are both used to investigate the transient response of the same model. The conductor is placed 10m above the ground, whose height and radius are 10m and 0.005m respectively. One end of the conductor is hang in the air and the other end is connected with current source of Gauss pulse type, as shown in Fig.3. The expression of the injected current source is written as E(t)= E_0exp[(t-t_0)^2/τ^2], where E_0=100A, t_0=4.5μs, τ=9μs.

The calculation results of the two methods are in good agreement. It indicates that the transient response of the thin conductor under various conditions can be investigated by using the method presented in this paper. Furthermore, other than being applied for these simple conductors, above method can also be used to analyze the transient electromagnetic response of arbitrarily deposited complicated structure conductor excited by various types of outer source.
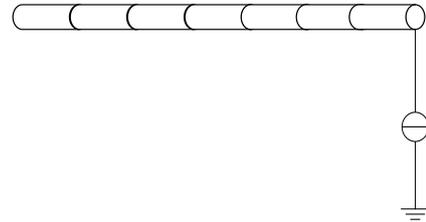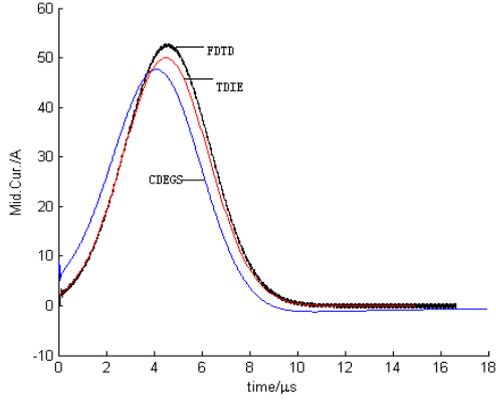

Figure 3. Computation model I

Figure 4.   Middle current of the conductor

IV.   SHADING EFFECTIVNESS

As an application, the shading performance of a construction to lightning is analyzed based on above method. The channel base current is expressed as double exponential function, that is

$$i(t) = 12.5 \times \left(e^{-\frac{1}{50 \times 10^{-6}}t} - e^{-\frac{1}{1.2 \times 10^{-6}}t} \right) kA \qquad (14)$$

The steel grid is considered to be of single layer and located in the center of the building. The space of the steel grid is set to be 15cm. Since the far field radiated from lightning is of interest in the study, the building is supposed to be 150km far from the lightning strike point.

A.   Effect of the Lightning Strike Position Relative to the building on Observed Magnetic Field

Different lightning strike position relative to the building is followed by different effect of the building on magnetic field at observation point. For the building of 50m high and 50m wide, as shown in Fig.5, two different lightning strike points are considered. Fig.6 shows the resultant lightning radiation magnetic field at 50m far from the building. Y-coordinate denotes the root-mean-square of the x-direction and y-direction magnetic field, x-coordinate denotes time. The red and blue curves express the results with and without consideration of the building respectively.
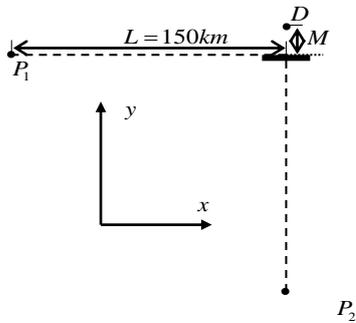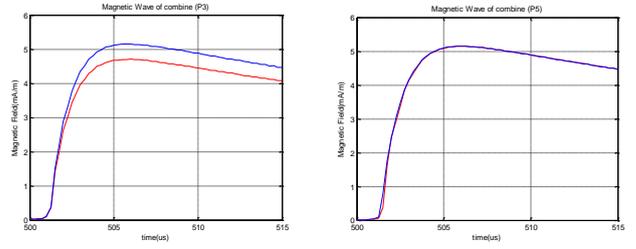

Figure 5.   Calculation model II

(a) lightning point is at P1 (b) lightning point is at P2

Figure 6.   Magnetic field at same observations point

It can be seen that, the magnetic field at observation point is influenced most significantly when the lightning strikes P1 (namely, lightning strike point is located at the extended line of the building, and the observation point is at the perpendicular line of the building). For the cases that lightning strike P1 and P2, the observed magnetic field vary slightly. Therefore, the following works is especially performed under the case that lightning strikes P1.

B.   Effect of the Building Height on Observed Radiation Magnetic field

With the building width set as 100m, the lightning radiation magnetic field at different distance from the building is shown in Fig.7. The building of 50m and 100m high, as well as the case without consideration of the building are all taken into account.

Note that for the same observation point, the effect of the building increase with its height. While with the increase of the distance from the building, the influence decreases accordingly, as generally known. In the range more than 200km far from the building, the observed magnetic is nearly independent of the building.
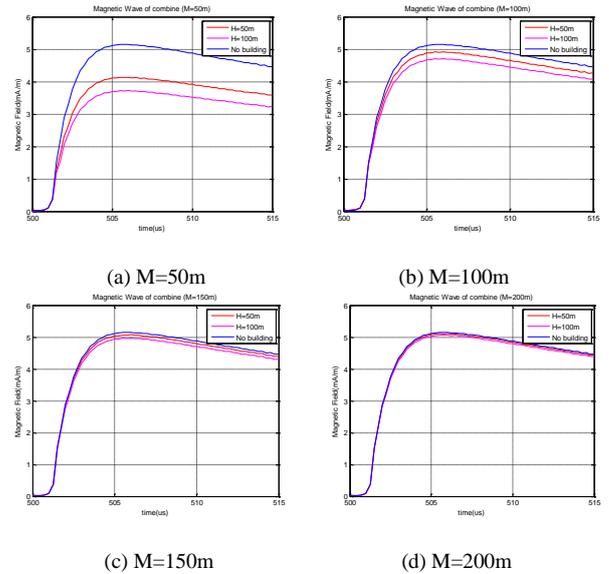

(a) M=50m   (b) M=100m

(c) M=150m   (d) M=200m

Figure 7.   Lightning magnetic field observed at different distance from the building for different height

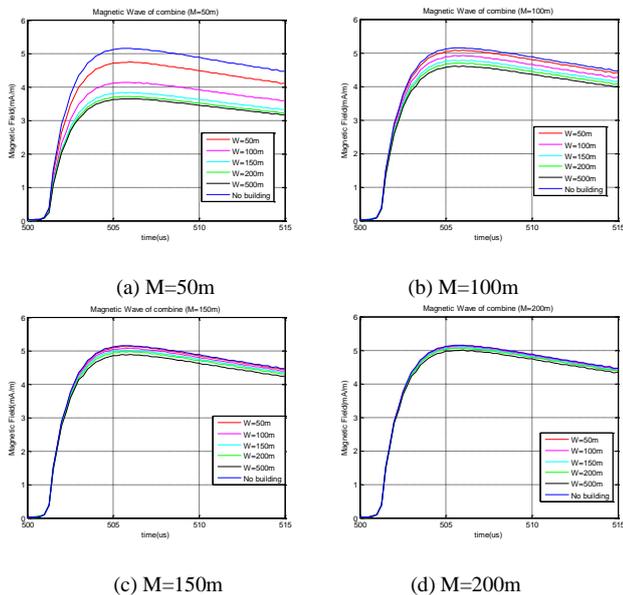(a) M=50m   (b) M=100m

(c) M=150m   (d) M=200m

Figure 8.   Lightning magnetic field observed at different distance from the building for different width

C. Effect of Building Width

With the height of the building set as 50m, the lightning radiation magnetic field at different distance from the building are shown in Fig.8. Different building width of 50m, 100m, 150m, 200m, 500m(such as building group), as well as the case without building are considered respectively.

Note that for the same observation point, the effect of the building increases with its width. While with the increase of the distance from the building, the influence decreases accordingly. It can be seen that:

1) The building of 200m wide results in nearly the same change with the building of 500m wide. There is a limit value for the effect of the building width.

2) The effect of the building on the magnetic field observed at more than 200m faraway can be neglected.

D. Effect of building on frequency-domain lightning radiation field

With the building height set as 50m, the building width set as 100m and 200m respectively, Fig.9 shows the lightning radiation magnetic field of different frequency at 100m above the ground. The distance from the observed point to the building is 50m.

It can be seen from Fig.9 that:

1) With the increase of frequency, the effect of building increase.

2) With the rise time of lightning current set as 1.2us，and the maximum frequency not more than 2MHz, in the frequency band lower than 2MHz, the effect of building is not significant. Therefore, previous calculation results do not display the change of rise time and arriving time.
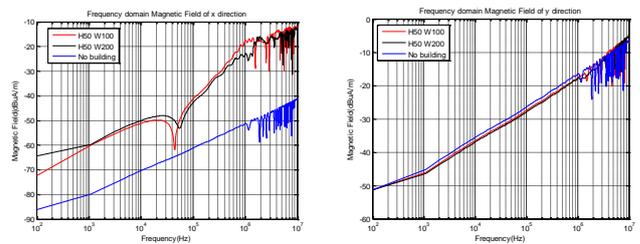

Figure 9.   amplitude-frequency of magnetic field at 50m far from the building considering building

3) In the low frequency range, the building does not modify the amplitude-frequency curve. Namely, the arriving time and rise time are affected slightly.

4) The effect of the building is primarily embodied on the peak value of the observed magnetic field.

V.   CONCLUSION

A rigorous method based on the method of moment applicable to the evaluation of shielding effectiveness of rectangular enclosure with aperture covered with wire grid is proposed. The method is validated by comparing the results with those obtained by using other methods. The presented approach can be used to analyze the shielding performance of protection cell in substation, and the shielding effectiveness of a typical protection cell model is calculated as an application. In addition, based on the comparison of different size of wire grid, the appropriate wire grid size can also be determined. Finally, it need to note that this method is not feasible for large problems, unless fast techniques (multiple expansion, hierarchical matrices, etc.) are used, for which the authors' further investigation is in process.

REFERENCES

[1]   P. Sewell, J. D. Turner, M. P. Robinson, and D. W. P. Thomas etc., "Comparison of analytic, numerical and approximate models for shielding effectiveness with measuremnet," IEE Proc.-Sci. Meas. Technol., vol.145, pp. 61-66, March 1998,

[2]   G. Cerri, R. De Leo, and V. M. Primiani, "Theoretical and experiment evaluation of the electromagnetic radiation from apertures in shielded evaluation," IEEE Transactions on EMC, vol. 34, pp. 423-432, Nov. 1992.

[3]   G. Manara, M. Bandinelli, A. Monorchio, "Electromagnetic penetration and coupling to wires through apertures of arbitrary shape," IEEE Trans. On EMC, vol.40, pp.391-396, Nov.1998

[4]   M. P. Robinson, T. M. Benson, C. Christopoulos, ect., "Analytical formulation for the shielding effectiveness of enclosures with apertures," IEEE Transactions on EMC, vol. 40, pp. 240-248, Aug. 1998.

[5]   N. N. Wang, J. H. Richmond, and M. C. Gilreath, "Sinusoidal reaction formulation for radiation and scattering from conducting surfaces," IEEE Trans. On A. P., vol.Ap-23, pp. 376-382, May,1975

[6]   Zhi Bin Zhao, Xiang Cui, Lin Li and Bo Zhang, "Analysis of the shielding effectiveness of rectangular enclosure of metal structures with apertures above ground plane", IEEE Transactions on Mag., vol. 41, pp. 1892-1895, May 2005

[7]   S. M. Rao, D. R.Wilton, and A.W. Glisson, "Electromagnetic scatteringby surfaces of arbitrary shape," IEEE Trans. Antennas Propag., vol. 30, no. 3, pp. 409–418, May 1982.

[8] S. U. Hwu, D. R. Wilton, and S. M. Rao, "Electromagnetic scattering and radiation by arbitrary conducting wire-surface configuration," IEEE APS Int. Symp. Dig., 1988, pp. 890-893

[9] H. Jeuland, B. Uguen, G. Chassay, and E. Grorud, "Numerical and experimental processes for the analysis of a wire antenna mounted on a metallic body," Microwave Opt. Technol. Lett., vol. 15, no. 5, pp.267–272, Aug. 1997.