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A Method of Line Fault Location Based on Traveling Wave Theory

Gang Ma[1, 2], Linru Jiang[1], Kaihua Zhou[1] and Guchao Xu[1]

1. School of Electric & Automation Engineering, Nanjing Normal University, Nanjing 210042, China
2. Electrical Engineering, Southeast University, Nanjing 210096, China
nnumg@njnu.edu.cn

Abstract

This paper combines traveling wave distance measuring principle with the wavelet transform and applies it to the detection and localization of power system short-circuit fault to avoid the severity and multiple of line short-circuit fault. Firstly, according to the current or voltage traveling wave signals detected by traveling wave detection devices put on the bus bar ends, we take traveling wave distance measuring principle as the theoretical basis to extract signals. Then, using wavelet transform to process the signal in order to extract the singular points. Also, traveling wave fault location is established by using B-type double-terminal traveling wave fault location algorithm. Finally, in order to locate the fault precisely and make simulation on different fault types and different sampling frequencies to come to a conclusion, we make wavelet transform of the transient fault signals and make further simulation about the location of single-phase grounding fault.

Keywords: *fault location, traveling wave fault location, wavelet transform, grounding fault, simulation*

1. Introduction

Power system is a pillar of the country's energy, also the economic lifeline. Determining the location of the failure point quickly and accurately after the transmission line failure can not only reduce the workload of line workers, but also help to clear the fault rapidly, which will ensure the stability of the power supply system [1]. Nowadays, the size of the grid is expanding, and operating conditions are becoming more and more complex. As a result, it is not easy to check out when failure occurs on the line. Thus, we need a method to locate the fault point quickly, efficiently and accurately. With the development of the traveling wave theory and modern mathematics, there has been some progress on the study of line failure based on traveling wave theory in recent years both at home and abroad.

The entire power grid cannot run without the power transmission lines of distribution network. Transmission line is a key to power transmission, also the point which causes the most times of mistakes in the entire power system. Long-distance transmission line and the variety of geography environment bring a lot of difficulties to trouble shooting. So, it is important to take an effective method to find the point of failure quickly, accurately, and reliably after a line failure [2-5].

Literature [6] proposed a fault location method which is based on impedance method. This method gets the distance to the failure point by calculating the AC impedance before and after the line fault happens, but it can be affected seriously by uncertain factors. Literature [7] proposed a ranging method of nonlinear frequency characteristics analysis, which uses nonlinear output frequency response function to analyze system domain characteristics. This paper proposes a dual-side traveling wave method based on traveling

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wave theory and wavelet transform theory, which gets the location of fault by analyzing the singular point of current or voltage traveling wave signal.

2. Double-ended Traveling Wave Principle

Voltage jump will occur on the fault point when ground fault occurs on the transmission line. The high-frequency current which is produced by voltage mutation on the line is defined as fault transient traveling wave on the transmission lines, whose speed is close to the speed of light. So we can take advantage of double-ended traveling principle to determine the point of failure.

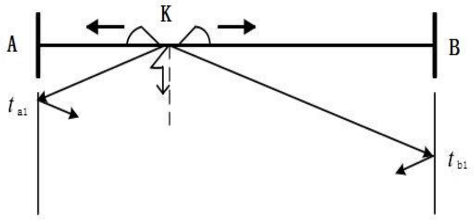


Figure 1. Schematic Diagram of Double Terminal Method

Double-ended power supply system is shown in Figure 1. The traveling waves produced by the fault point will spread to both ends of the line when ground fault occurs on the transmission line. We can calculate the distance to fault point by using the time difference of traveling-wave arrival at the line ends. Point K in the figure is the point of failure, t_{a1} and t_{b1} are the initial times for transient traveling wave reaching A-side and B-side of line respectively. The velocity of traveling wave is v, the total length of the line is L_{AB}, the fault location can be expressed as:

$$D_{AK} = \frac{L_{AB} - v(t_{b1} - t_{a1})}{2}$$

$$D_{BK} = \frac{L_{AB} + v(t_{b1} - t_{a1})}{2} \qquad (1)$$

Double terminal method uses the traveling wave produced by line fault to locate the fault point. In this paper, we use traveling wave recording device which is mounted on the bus side of the transformer to capture and record the initial traveling wave. Then, analyze the time when initial traveling wave arrives at the bus side of transformer by using computer wavelet transform. This method converts the complex problem of locating line fault to a relatively simple physical problem about distance.

3. Double Terminal Method of Traveling Wave Fault Location

The method of locating fault point based on two-terminal traveling wave theory is different from the method based on two-terminal electrical quantities [8], which measures and locates point by the change of voltage, current and other parameters on both ends of the line. Double-terminal traveling wave method only needs the time of fault traveling wave reaching both ends of the line, and the speed of light is approximate to the velocity of the traveling wave. As a result, it has advantage on simplified calculation.

3.1 Extraction of Traveling-wave Signal

The key to realize two-terminal traveling wave method lies in the ability of capturing the traveling wave when it reaches both ends of the transmission line. When transmission line fault occurs, we can find the change of voltage and current obvious on the primary side, then line wave surge generates, which contains lots of information about the line fault. It is important to choose a simple and economical way to survey the fault traveling wave signals from the secondary side of the transformer because we need to survey it.

Only after the cutoff frequency of current and voltage transformer is higher than 10KHZ has been confirmed can we collect the slightly distorted signal while the frequency of fault traveling wave is high. Also, it is better for traveling wave distance measuring device to share transformers with other protection devices such as distance protection and differential protection, or it will be difficult to promote due to its poor economy. In order to meet the demand of accuracy within 1km, the rising edge time of the signal on the secondary side should be less than a few microseconds [11]. According to the experiment, the high-voltage transformer is unable to meet this requirement, while transient response speed of current transformers can meet the measurement request of high-frequency fault traveling waves.

It is necessary to determine the arrival time of the initial surge by analyzing the traveling wave signal after the signal acquisition conditions are met. The signal is of singularity at that point if a signal or a derivative is off somewhere; If the signal is unlimited derivative in its domain of definition, then the signal is none of singularity, a mutant signal must be singular at its mutant point.[12]

The traveling wave signals from the line fault are almost mutant signals. The waveform will change to be intermittent when fault happens. The key to determining the time of fault occurs is to find the singular point of the signal. In order to analyze the traveling wave signal, this paper takes the method of wavelet transform, which is sensitive to frequency when processing the discrete signal. When the frequency of wave signal mutates, the wavelet transform will change. The arrival time of initial surge traveling wave at both ends can be known according to the changes, the sampling frequency and the starting and ending time. Then we can calculate absolute time difference by using time synchronization devices on both ends.

3.2 Synchronization of Two-side Fault Signal

The key to the method which is used in this paper is to determine absolute time difference for initial surge of current traveling wave on both ends of the transmission line to reach the bus. So, it is necessary to build a communication channel which can meet request of speed and unconditional simultaneity on both ends of line. With the development of global positioning system (GPS), synchronous sampling on both ends of line has become a reality.

The transmission line is equipped with GPS synchronization device and communication equipment based on wireless base station on both ends, which can make sure that data will be analyzed accurately in real time. In order to meet sampling frequency of the traveling wave signals, we can take the technology of GPS synchronized sampling to ensure a high degree of synchronous sampling, whose maximum error is less than 1us. The GPS synchronized sampling device is shown in Figure 2 [13].

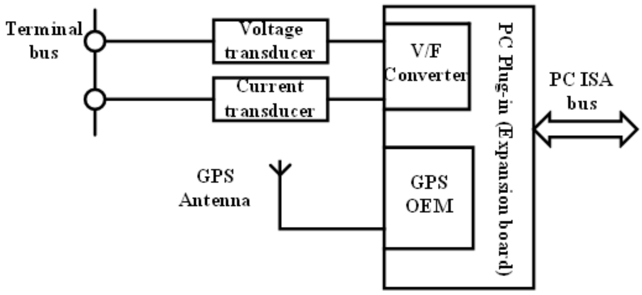


Figure 2. Synchronized Sampling Device

As we can see in Figure 2, the device is equipped with a PC bus, which can transform analog quantity collected by transformer based on GPS synchronization technique to digital quantity by converter, then input the signal to the computer through the plug-in unit, so we can get clock synchronized fault signals on both ends.

4. Algorithm for Double Terminal Theory of Traveling Wave

4.1 Fixed Wave Velocity

Specific steps of the algorithm are shown in Figure 3:

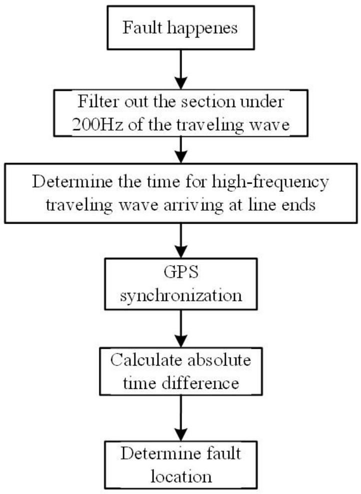


Figure 3. Double-ended Traveling Wave Flow Chart

Set up the head and the end of the fault line as A-side and B-side. When a fault occurs, the time of initial traveling wave reaching A-side and B-side are t_{a1} and t_{b1} respectively. v is traveling wave velocity, then the fault location can be figured out by using equation(1).

According to the equation, the distance of transmission fault is determined by the wave velocity, the total length of the line and the time difference of initial traveling wave surge arriving between both ends of the line. Double terminal method of traveling wave fault location uses fixed traveling wave velocity to measure the distance, also the real length of the line is L_{AB}. As a result, the deviation of calculation is almost determined by the deviation of initial surge of traveling wave arrival time difference between the two ends of the line.

4.2 Improve the System to Reduce Velocity's Impact

The traveling wave velocity in equation (1) is fixed. In fact, the unit inductance and capacitance of line will change when considering the impact result from topography and climate changes. According to the equation of velocity $v = 1/\sqrt{L \cdot C}$, the actual wave velocity may change. At the same time, it is difficult to select the velocity directly for the reason that the velocities of traveling wave in the line are different at different frequencies. Based on the above reasons, we can see that there are great uncertainties over the velocity of traveling wave. So, it is important to determine the velocity of wave if we want to improve the accuracy of the method of traveling wave fault location.

In order to reduce the effect of wave velocity, we use a double terminal method of traveling wave fault location based on the real-time measured wave velocity in this paper. Because of the method we use, the line in measuring area is uniform, the wave velocity in measuring area is determined by the equipment based on the double terminal method and line out of measuring area.

When a grounding fault occurs on the line out of the measuring area, the wave velocity from the fault point can run through the power line in measuring area. Assume l as the total length of the line, t_1 and t_2 are assumed as the time of initial fault traveling wave out of the measuring area to reach the traveling wave recording devices on both ends of the bus, so we can define the velocity of traveling wave in measuring area is:

$$v = \frac{l}{|t_2 - t_1|} \tag{2}$$

When fault location outside the measuring area is too far or there is too much attenuation of signal in the process of transmission, a large error will occur in the recording traveling data. Now, compare the measured velocity with the theoretical velocity. If the error is in the scope allowed, then we should take this data, otherwise we should abandon it and do not modify the last record. So we can not only ensure the accuracy of the wave velocity and realize the measurement of velocity online, but also improve the economy so that we don't need to add equipment.

Actual measurement of velocity can also be measured by injecting signal in offline mode when the line is under construction. The measured velocity is more close to theoretical velocity, however, there must be some deviation because the noise is added in actual operations.

Substitute equation (2) into equation (1), then we can get the formula of the fault distance:

$$D_{AM} = \frac{l}{2} \cdot \left[1 + \frac{t_{a1} - t_{b1}}{t_2 - t_1} \right] \tag{3}$$

According to the sag rate of power line and the fault distance calculated by the above formula, we can find the tower number of the fault line accurately, and the affection of tower location which is caused by wave velocity can be eliminated in some ways.

5. Simulation

In this experiment, we use Simulink in Matlab to create a simulation system. Assume the length of a 10kV double terminal power line as 500km, now the A-phase grounding fault occurs at 100km from the start point of the line. We can see the model of the line distributed parameter in Figure 4.

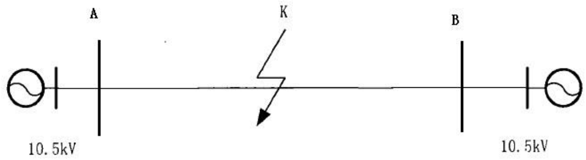


Figure 4. The Model of 10kV Double Terminal Power Supply

Use powerlib, one of the power system modules in Simulink toolbox to build model transmission line model, which is shown in Figure 5.

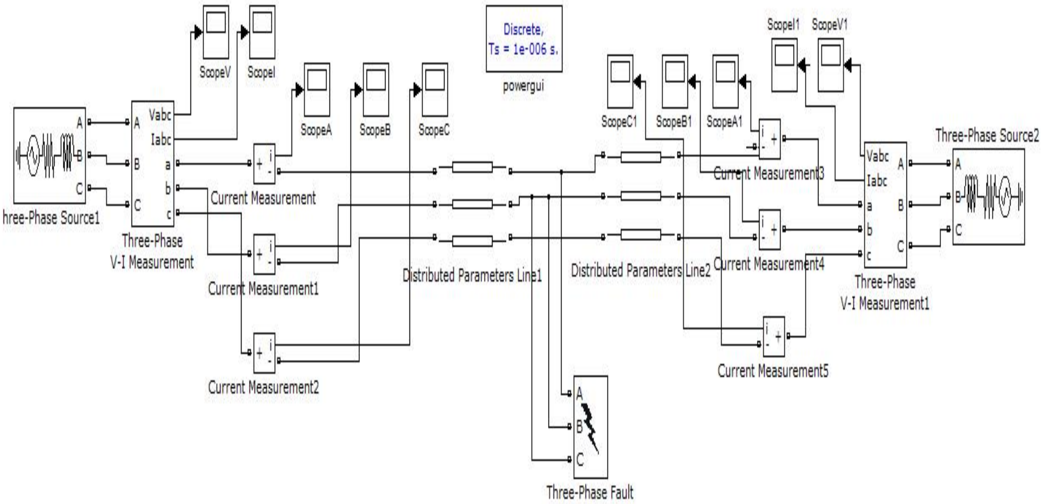


Figure 5. 10kV Transmission Line Simulation Module

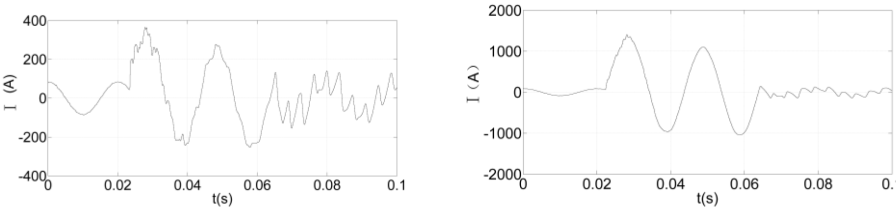
As we can see in Figure 5, the three-phase power supply in the system is set as 10kV, 50Hz and neutral grounding. The wiring structure of the transformer is Y/Yg. The parameters of line are as follows:

$$r_1 = 0.0127\Omega / km, l_1 = 0.934 \times 10^{-3} H / km, c_1 = 12.74 \times 10^{-9} F / km,$$
$$r_0 = 0.384\Omega / km,\ l_0 = 4.126 \times 10^{-3} H / km, c_0 = 7.75 \times 10^{-9} F / km,$$ the total length of line is 500km.

In order to meet the accuracy of time to complete the simulation, we set the powergui parameter in the figure as discrete sampling mode and set the sampling frequency as 1MHz.

5.1 Single-phase Grounding Fault Simulation

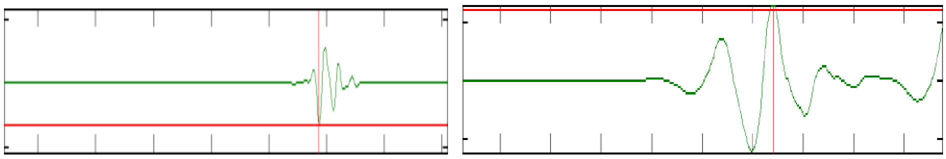
Make a single-phase grounding fault simulation at the point which is 100km far away from the point A, then we can see fault current waveform from the transformers at both ends of the transmission line, such as Figure6 (a),(b).



(a) A Terminal Waveform (b) B Terminal Waveform

Figure 6. The Current Waveform of Single-Phase Grounding Short Circuit

Based on wavemenu wavelet transform module in Matlab, five layers of discrete dyadic wavelet transform is made on the collected discrete fault current signal by using db5 as wavelet function. We can see the waveforms shown in Figure 7 (a, b).



(a) A Terminal Signal Waveform (b) B Terminal Signal Waveform

Figure 7. The Traveling Waveform of Single-phase Fault

The initial time of transient traveling wave reaching A-side and B-side of the line is easy to get according to the waveform after transformation, which is the time of waveform distortion point on the positioning line shown in waveform. We can see that t_a is 22369 in Figure 7(a) and t_b is 23373 in Figure 7(b).

We can calculate the fault location by using equation (1):

$$t_{a1} = 22369 \times 10^{-6}\,\text{s}$$

$$t_{b1} = 23373 \times 10^{-6}\,\text{s}$$

$$\Delta t = t_{b1} - t_{a1} = 23373 \times 10^{-6} - 22369 \times 10^{-6} = 1004 \times 10^{-6}\,\text{s}$$

$$D_{AK} = \frac{L_{AB} - v(t_{b1} - t_{a1})}{2} = \frac{500 - 3 \times 10^{5} \times 1004 \times 10^{-6}}{2} = 99.4\,\text{km}$$

The distance from then fault point to a terminal measurement point is 99.4km, the absolute error of this simulation is 600m and the relative error is 0.6%.

Make the same simulation experiment to the fault point which is 300km away, we can see that t_a is 23022 and t_b is 22691 by using traveling wave extraction and wavelet transformation.

According to equation (1), we get the fault location:

$$t_{a1} = 23022 \times 10^{-6}\,\text{s}$$

$$t_{b1} = 22691 \times 10^{-6}\,\text{s}$$

$$\Delta t = t_{b1} - t_{a1} = 22691 \times 10^{-6} - 23022 \times 10^{-6} = \text{-}331 \times 10^{-6}\,\text{s}$$

$$D_{AK} = \frac{L_{AB} - v(t_{b1} - t_{a1})}{2} = \frac{500 - 3\times10^{5}\times(-331\times10^{-6})}{2} = 299.65\text{ km}$$

The distance from fault point to A terminal measure point is 299.65km. The absolute error is 350m and the relative error is 0.117%.

The above simulation shows that double terminal method of traveling wave fault location is effective to the single-phase grounding fault in 10kV double terminal power supply system. The method can locate the fault points effectively, and the range of error to the fault location is small.

In order to test and verify the effectiveness of the method of traveling wave fault location which is mentioned in this paper, we select the distance to the fault randomly to verify the effectiveness and accuracy of the method when single-phase short circuit, phase-to-phase short circuit or three-phase short circuit happens. The result of simulation is shown in table 1.

Table 1. The Result of Fault Simulation

Fault type	Fault distance/km	Time difference/ μs	Fault distance/km	Absolute error/m	Relative error/%
One-phase	80	1135	79.75	250	0.25
	230	135	229.75	250	0.25
Two-phase	80	1130	80.5	500	0.5
	230	129	230.65	650	0.65
Three-phase	80	1131	80.35	350	0.35
	230	130	230.5	500	0.5

According to the data from the above table we can find that, the method of traveling wave fault location we use in this paper is also an effective way to locate fault point in other types of fault.

5.2 Impact Made by Sampling Frequency to the Ranging Error

The sampling frequency of fault traveling wave has a deep effect on the result of calculation according to the principle of traveling wave fault location. When the sampling frequency is high, if the period of sampling become shorter, the accuracy of Δt will improve and then accuracy of calculation result will also rise.

In order to test the influence of frequency on the measuring error, we choose different sampling frequency such as 1MHz, 5MHz and 10MHz to make simulation of traveling wave fault location respectively. The specific results can be found in Table 2.

Table 2. The Effect of Sampling Frequency on Simulation Results

Single-phase grounding fault	1MHz		5MHz		10MHz	
	80	230	80	230	80	230
Time difference/μs	1135	135	1134.2	132.8	1133.7	133.5
Fault distance/km	79.75	229.75	79.87	230.08	79.945	229.975
Absolute error/m	250	250	130	80	55	25
Relative error/%	0.25	0.25	0.13	0.08	0.055	0.025

From the data in the table we can see that the effect of sampling frequency on simulation results. When the sampling frequency increases, the accuracy of location also increases. For example, the sampling error is 300m when the frequency is 1MHz, the sampling error is 100m when the frequency is 5MHz and the sampling error is down to 50m when the frequency is up to 10MHz.

The increase of sampling frequency may improve the accuracy of the method in some ways. However, with the increase of sampling frequency, the strong hardware is needed. The requirement of sampling channel, fault-tolerant processing and database will increase, and the huge sampling data will make calculation become more complicated. So, we should take different factors into account and determine a reasonable sampling frequency to meet the actual error requirement.

6. Conclusion

This paper presents a double terminal method of traveling wave fault location to find the fault point when line fault occurs, and uses simulation software to do some simulation experiments, which proves that the method can locate the fault point effectively, precisely, and feasibly. The method can work out the distance to the fault point by determining the times of initial traveling wave reaching both ends of line. Therefore, the excessive resistances, grounding resistance, the reflection and refraction of traveling wave have no effect on the method, so it has the characteristics of high accuracy and small calculation. It can theoretically reduce or even eliminate the effect of wave velocity on the accuracy of measurement by using double terminal method to measure velocity.

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References

[1] Y.H. Bao, “Study on Full Parallel AT Power Supply Mode Protection and Fault Location Plan”, Electric Railway, vol. 2, **(2010)**, pp. 15-19.
[2] Z. Li, Z. Feng and L. Jun, “Fault locating based on single-end traveling waves for T-type transmission lines”, Electric Power Automation Equipment, vol. 30, no. 4, **(2010)**, pp. 46-50.
[3] X. Fei, D. Xinzhou and W. Bin, “Combined single-end fault location method of transmission line and its experiments”, Electric Power Automation Equipment, vol. 34, no. 4, **(2014)**, pp.37-42.
[4] Z. Zhou, L. Yanping and W. Jie, “A new two-terminal traveling wave fault location method based on wavelet transform”, Power System Technology, vol. 34, no. 1, **(2010)**, pp.203-207.
[5] S. Xue, J. He and Y. Li, “Analysis of Unified Traveling Wave Theory for Transmission Lines”, Automation of Electric Power System, vol. 31, no. 20, **(2007)**, pp. 32-35.
[6] R. Zheng, X. Lin and F. Zhao, “Fault location based on global search of minimum phase difference for high voltage transmission lines”, Electric Power Automation Equipment, vol. 32, no. 3, **(2012)**, pp. 58-61.
[7] C. Minyou, S. Feng and Z. Jinqian, “The online monitoring method of power transmission line fault based non-linear frequency response function”, Journal of Chongqing University, vol. 33, no. 1, **(2010)**, pp. 54-60.
[8] H. Shu, C. Cheng and W. Zhaoet, “Accurate traveling-wave front detection based on morphology and HHT”, Electric Power Automation Equipment, vol. 29, no. 7, **(2009)**, pp.1-7.
[9] Q. Jian, “Study on single terminal travelling wave fault location of transmission line”, Power System Technology, vol. 29, no. 15, **(2005)**, pp. 65-70.
[10] W. Geng, M. Huaning, “Fault location methods based on travelling wave theory for high voltage power transmission lines”, High Voltage Apparatus, vol. 4, no. 2, **(2005)**, pp. 135-138.
[11] S. Hongchun, L. Yi and X. Yingxia, “Discussions on the single ended approach based on travelling wave to fault location that can avoid the effect of wave speed”, Relay, vol. 34, no. 8, **(2006)**, pp. 1-2.

[12] J. Yu, J. Yanjun and W. ZengPing, "New Principle of Fault Phase Selection Based on Wavelet Filter and Its Derived Filter", Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific. IEEE, **(2012)**, pp.1-4.
[13] S. Zhenhong, Z. Ju and T. Jie, "Fault location based on dual-terminal voltage measurement", Electric Power Automation Equipment, vol. 26, no. 6, **(2006)**, pp. 27-29.

Author

Gang Ma, He is a lecturer in School of Electric & Automation Engineering, Nanjing Normal University. He received the Ph.D. degrees from North China Electric Power University. His research interests include renewable energy, power system analysis & simulation and Smart Grid.

