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Spatiotemporal multifractal characteristics of electromagnetic radiation in response to deep coal rock bursts

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Abstract

Dynamic collapses of deeply mined coal rocks are severe threats to miners, in order to predict the collapses more accurately using electromagnetic radiation (EMR), we investigate the spatiotemporal multifractal characteristics and formation mechanism of EMR induced by underground coal mining. Coal rock in the burst-prone zone often exchanges materials and energy with its environment and gradually transits from its original stable equilibrium structure to a non-equilibrium dissipative structure with implicit spatiotemporal complexity or multifractal structures, resulting in temporal variation in multifractal EMR. The inherent law of EMR time series during damage evolution was analyzed by using time-varying multifractal theory. Results show that the time-varying multifractal characteristics of EMR are determined by damage evolutions process, the dissipated energy caused by damage evolutions such as crack propagation, fractal sliding and shearing can be regarded as the fingerprint of various EMR micro-mechanics. Dynamic spatiotemporal multifractal spectrum of EMR considers both spatial (multiple fractures) and temporal (dynamic evolution) characteristics of coal rocks, and records the dynamic evolution processes of rock bursts. Thus, it can be used to evaluate the coal deformation and fracture process. The study is of significance for us to in-depth understand EMR mechanism and to increase the accuracy of applying the EMR method to forecast dynamic disasters.

1 Introduction

With coal mining deepening, dynamic disasters such as rock burst and roof collapse become increasingly severe, threatening mine safety and efficient production. Monitoring and forecasting coal rock dynamic disasters have become the key issue to be resolved. Since the discovery of electromagnetic emission (EM) from materials during their deformation and fracture (Nitsan, 1977; Warwick et al.1982; Ogawa et al., 1985; Brady et al., 1986; Cress et al., 1987), electromagnetic radiation (EMR) was widely

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applied to monitor and forecast seismic and **dynamic disasters** (Warwick et al., 1982; Vallianatos and Tzanis, **1998a, b**, 2003; Tzanis and Vallianatos, 2001, 2002; Vallianatos et al., 2004; Eftaxias et al., 2003; Frid, 2005; Contoyiannis et al., 2005; Wang Enyuan et al., 2012; He et al., 2012; Potirakis, 2012). The critical phenomena and fractal characteristics of EMR were observed before seismic or rock fracture (Hayakawa et al., 2004; Rabinowitch et al., 2001; **Hadjicontis, 2003**; Uritsky et al., 2004; Kapirs et al., 2004a, b; Gotoh et al., 2004; Eftaxias et al., 2007; Jun Muto et al., 2007). Some scholars considered that the critical phenomena of EM emission were related to crack opening and expansion, **as well as fractal** structure (Hayakawa et al., 2004; Nanjo et al., 2004a, b; Kapirs et al., 2004a, b; Morgounov and Malzev., 2007; Kawada et al., 2007; Minadakis et al., 2012). Uritsky et al. (2004) propose a simple framework for modeling ultra-low frequency (ULF) electromagnetic emission signals associated with abrupt changes in the large-scale geometry of stress distribution before characteristic seismic events. Kapirs (2004) found that the critical characteristics of EM were determined by the nonlinear multi-fracture of discrete materials. Kawada (2007), from the thermodynamic view of irreversible damage evolution, introduced dipoles and explained theoretically the critical phenomena of EM emission and its time-scale invariance. These researches are of significance for the explanation of EMR critical characteristics before seismic or during rock fracture.

Moreover, EMR emitted before seismic or in the process of rock failure not only has critical characteristics, experimental and in-situ observation data also show that the EMR time series exist characteristics of the time-varying fractal dimension, change in entropy, and multifractal (Wei et al., 2005; Eftaxias et al., 2007; Potirakis et al., 2012; Minadakis et al., 2012). Eftaxias et al. (2007) analyzed the fractal spectra of a large number of pre-burst EMR signals and nonlinear approximate entropy, and found that the fractal dimension and approximate entropy changed with time. **Besides, many scholars performed multi-disciplinary analyses of criticality** (Eftaxias et al., 2003; Kapiris et al., 2004a; Contoyiannis et al., 2005) **and complexity** (Eftaxias et al., 2007), and found that during coal rock fracturing, EMR intensity increased in a power manner, while just

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before global ruptures of various scales occurred from rock failure to crust collapse, EMR underwent a very complex, intensity-increasing process. Vallianatos et al. (Vallianatos and Tzanis, 1998a, b, 2003; Tzanis and Vallianatos, 2001, 2002; Vallianatos et al., 2004) proved a promising effect that is ubiquitous during brittle rock failure: the motion of charged edge dislocations (MCD) during crack opening and propagation (microfracturing). Vallianatos, et al. (2004) assumed that when ionic crystals and rocks undergo such drastic changes, more than one electrification mechanisms may be operative. These findings imply that EM emission is acted jointly by many mechanisms and changes dynamically with the system developing. The solid deformation and fracture are a multilevel self-organized process, in which changes in internal structure at micro-, meso- and macro-levels are organically linked. During the damage evolution of such a system, cracks at various scales coexist and simultaneously occur, resulting in the emission of very complex EMR. In short, linear and multiple fractures of solid materials will lead to a dynamic, nonlinear EMR fluctuation.

Coal rocks as a natural discrete medium and sedimentary materials have many defects such as stratification, joints, pores, fractures, etc. Dynamic disasters, such as rock burst and roof collapse, are instantaneous, instable phenomena occurred in coal rocks under the effects of external physical, and chemical factors, or stress. Along with the instable process, EMR is generated and emitted. Studies have found that EMR intensity and activity are significantly enhanced with rock burst risks increasing (etc. Frid, 2005; Wang et al., 2012; He et al., 2012). Field observations and experimental studies also showed that rock burst is a open and dissipative system with complex structures and behaviors and can exchange energy with external environment (Lu et al., 2004, 2007). Song et al. (2012) had applied the dissipative structure theory to study energy accumulation, dissipation and entropy changes during coal and rock deformation and failure and found that the energy accumulation and dissipation possess self-organized criticality (SOC). Similar to the multiple nonlinear rupture process of discrete media, EMR generation is accompanied with coal rock dynamic evolution, and carries the fingerprint information of the system instability or rock burst, thus it occurs before coal rock fail-

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ure and burst. However, investigating the electromagnetic responses to underground geodynamic processes, particularly the pre-seismic and seismic processes, is a challenging task in modern geophysics. Increasing evidences have shown that it is difficult to quantitatively describe seismic electromagnetic (SEM) phenomena by “linear” models using “averaged” parameters. Because coal rock system is highly inhomogeneous (at all scales) and anisotropic, the effective way to describe it is via non-linear theory.

Experimental and theoretical evidences have shown that disordered media in critical, instable phase posses an implicit spatiotemporal complexity, which could form fractal structures at multiple scales, which is similar to the non-equilibrium phase transition process (Eftaxias et al., 2003, 2007). Thus, the fractal dimension and its relevant index can be used as a indicator to analyze the characteristics of the system. For example, spatiotemporal dynamical characteristics of the instable, nonlinear system during the dynamic evolution process could be revealed using windowed multifractal singular spectrum and temporal multifractal spectrum (Wang et al., 2001; Masao et al., 2007; Gang et al., 2012).

Real-time online EMR monitoring is the basis for studying the mechanisms and characteristics of EMR from coal rock bursts during underground coal mining. We have previously developed a KBD7 online real-time EMR monitoring instrument and widely applied it to predict coal and gas outbursts and rock bursts in mines and mining faces (Wang et al., 1997, 2011, 2012; He et al., 2012). Based on real-time field monitoring data, in this paper, we analyzed EMR temporal multifractal spectrum to explore the mechanisms for EMR generation in the process of rock burst evolution, investigated the temporal response characteristics of EMR generated by coal rock burst during underground mining, revealed the nature of nonlinear, dynamical EMR changes, and further discussed the temporal EMR multifractal practicability. The results are of great significance for further understanding the rock burst mechanisms and improving the reliability of EMR monitoring and early warning.

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2 Instrumentation

2.1 EMR data acquisition system

EM from coal rock is the electromagnetic energy generated during the deformation and failure of coal rock and closely related to the process of coal rock deformation and failure. EMR could comprehensively reflect the effects of the main factors on dynamic disasters such as rock burst and roof collapse among others, and on the degree of coal rock deformation and fracture under load. To this end, we designed and developed an EMR monitoring instrument and used it to measure the EMR generated due to coal rock deformation and failure in the working face and to predict coal rock dynamic disasters, shown as Fig. 1.

Figure 1 displays the KBD7 online EMR monitoring instrument, the detailed parameters refer related literature (Wang et al., 1997, 2011, 2012; He et al., 2012). It consists of a highly sensitive, directional reception antenna, a host computer, a remote communication interface and a transmission cable and has major functions including data collection, conversion, storage, and processing, as well as communication and alarming. In addition, the explosion-proof design guarantees its security in applications. Figure 2 showed the KBD7 Coal and rock dynamic disasters non-contact EMR monitor principle diagram.

The signal collection, conversion, processing, storage and output are done automatically and continuously by KBD7 monitoring system. The EMR signals received by the antenna 1 can not be processed directly because they are too weak. They are amplified by the preamplifier 2, converted by A/D converter 3, and deposited in the cache 4. The data in the cache could be read out by CPU 5 and stored in data memory 7. The monitoring data can be displayed on the LCD display 8 in real time. The monitor can work either alone through external power supply or together with KJ coal mine safety monitoring system. A self-developed application software is installed in the computer at the monitoring center and control terminals and can be easily used for real-time EMR acquisition, display and analysis.

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2.2 Instrumentation

To use the instrument, one needs to first set the EMR-receiving antenna facing key monitoring areas on the working face, such as the stress concentrated area, advancing face and geologic structure zone. The EMR signals attenuation can be influenced by electrical parameters of coal and rock (resistivity/conductivity), coal mechanical parameters, composition, the stress state of the coal seam, gas and moisture content. Therefore, the signals attenuate sharply when the signals propagate outward through the surrounding coal and rock. The monitoring areas of EMR are limited due to the high signal attenuation. EMR signals generated by coal and rock deformation and fracture mainly belong to low frequency signal. According to electromagnetic theory, the frequency of the maximum power point of EMR changes over distance of radiation source, frequency varies inversely as the square of the distance. Make spectrum analysis for the recorded EMR signal, determine the frequency of the max power radiation, then we could effectively predict the distance of EMR radiation source. The specific derivation was given out in literature (Wang Enyuan et al., 2009). All of the above factors would affect the EMR antenna layout.

According to the literature (Wang Enyuan et al., 2009), the most suitable distance between the antenna and the measured area is equal to or less than 5 m, depending upon the size of the monitoring area, which has to locate in the opening direction of the antenna. The monitoring distance or range of each antenna is about 20 m, therefore the measuring points are set every 10 m to 20 m in the working face. For those zones of greater rock burst risk, the measuring points should be arranged as more as possible. The monitor can work either alone through external power supply or together with KJ coal mine safety monitoring system. ~~A self-developed application software is installed on the computer at the monitoring center and control terminals and can be easily used for real time EMR acquisition, display and analysis (see in Fig. 3).~~

In this study, the system is set up to record EMR data every 15 s and the whole signal transmission process predicting rock burst and roof collapse is as follows: (1)

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receive EMR signals by directional antenna, (2) after amplification, store the electric signals in the buffer zone, filter noises, and perform analog-digit transformation; (3) conduct statistics analyses, and output the standard signals (1–5 mA, 4–20 mA or 200–1000 Hz); and (4) transfer data to the central computer via KJ31 coal mine safety monitoring system.

3 Observation results

The first field investigation on rock burst was conducted at Coal Mine A located in Henan Province, China. It occurred during excavation at No. 23150 mining face of the bolted roadway before dawn on 12 March 2013 causing great damages to the roadway long up to 50 m, slight roof sinking, upheaval of 0.8 m floor, 0.8 m displacement of roadway's both sides, and deformation of the supports at different degrees. Figure 4 shows the layout of EMR monitoring antenna in the advancing roadway.

Figure 5 shows the variation of EMR during the excavation of No. 23150 roadway. With the heading face gradually closing to the stress concentrated area of the northern rail, the stress applied on coal rock increased, and EMR from coal rock enhanced obviously. From 6 March to 10, EMR intensity increased about three-fold from its basal level of 18 mV to the peak of 60 mV, and the measured EMR varied fiercely. The signal intensity decreased to 20 mV on 11 March, and the rock burst occurred in the excavation roadway before dawn on 12 March. Before the rock burst, the signals increased once again and showed the super-critical phenomenon from 10 March to 11 March, indicating that the mining face had entered the dangerous zone where coal rock was prone to bursts. The rock burst occurred in the advancing roadway two days after appearance of the super-critical phenomenon. In addition, EMR intensity showed a decreased trend two days before the occurrence of the rock burst after reaching its peak.

EMR intensity is affected by different stope backgrounds. Figure 6 shows dynamic variation of EMR generated from the coal rock of bolted roadway at the driving face of Coal Mine B. Here, EMR intensity was mainly affected by mining-induced stress. The

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critical value of EMR was 150 mV, which was very different from that obtained from the mining roadway of Coal Mine A. It is known from Fig. 6 that the EMR increased obviously after 8 a.m. On 3 November 2011, and its basal level exceeded the critical value. At 19:45 on that day, the rock burst occurred in the bolted roadway when EMR was increasing, causing severe deformation of the roadway.

The above two typical examples indicated that when abnormal EMR signal is an indicator of rock burst regardless its location, either the mining face or the heading face and affected by the coal rock mechanical properties, coal seam geological structure, working environment, etc. Thus, it is reasonable that EMR signals from different working faces are different. Wang et al. (2011) have proved that rock burst could occur when EMR intensity changes, either increase or decrease, making it very difficult to monitor and pre-warn rock burst. ~~Therefore, monitoring and early warning of rock burst.~~ So it is necessary to further analyze the nature and inherent laws of the nonlinear dynamic characteristics of EMR during the spatiotemporal evolution of rock burst.

By contrast, an EMR time series was also recorded from regions that no damages were developed (see in Fig. 7). It can be seen in Fig. 7, the electromagnetic radiation energy stays at a low level, with a slight fluctuation, in non rock burst hazard area.

4 Temporal characteristics of EMR from coal rock burst

4.1 Temporal multifractal spectrum of EMR and its physical meanings

EMR can reflect the deformation and failure process of coal rocks and reveal spatiotemporal dynamic characteristics of coal- and rock-induced damages. Experimental and theoretical evidences show that at their critical, instable phase, the spatiotemporal complexity of disordered media will present themselves, generally forming a multi-scale fractal structure similar to the transition process of non-equilibrium phase (Eftaxias et al., 2003, 2007).

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Assuming that an EMR time series $\{x_i\}$ can be divided into N subsets of length ε , the probability distribution of each subset is calculated as $\{P_i(\varepsilon)\}$. If the time series meet multi-fractal characteristics, the probability distribution function $\{P_i(\varepsilon)\}$ and divided scale ε as $\varepsilon \rightarrow 0$ obey the following equation:

$$\{P_i(\varepsilon)\} \propto \varepsilon^\alpha \quad (1)$$

where α is a constant known as the singularity exponent, controlling the singularity of the probability function $\{P_i(\varepsilon)\}$, and reflecting the various divided scale ε of the time series and the properties of various subset whose probability distribution function changes with the divided scale ε changing, i.e. The non-uniformity of a subset probability.

If the number of units with the same probability in the subsets marked by α is denoted as $N_\alpha(\varepsilon)$, generally speaking, the smaller the divided scale ε is, the more the number of subsets obtained. Hence, $N_\alpha(\varepsilon)$ increases with ε decreasing and meets the following relationship:

$$N_\alpha(\varepsilon) \propto \varepsilon^{-f(\alpha)} \quad (2)$$

where $f(\alpha)$ is the frequency of the subset represented by α in the whole subset collection, that is, the fractal dimension of α subset.

However, practically, it is difficult to calculate using the definition. At present, statistical physics method is generally applied to compute multi-fractal spectra. First, a partition function, i.e. the statistical moment is defined as follows

$$X_q(\varepsilon) \equiv \sum P_i(\varepsilon)^q \sim \varepsilon^{\tau(q)}, \quad (3)$$

where $\tau(q)$ is the quality index, with $-\infty < q < +\infty$. In actual calculation, when $|q|$ reaches some definite value, the multifractal spectrum tends to be stable; after that, even at greater values. Generally, the value q is defined within a certain range.

As the equality in Eq. (3) holds true, that is, the defined partition function X_q is the power function of the divided scale ε , the quality index $\tau(q)$ can be obtained by calculating the slope of the double logarithmic curve, $\ln X_q(\varepsilon) - \ln \varepsilon$, i.e.,

$$\tau(q) = \lim_{\varepsilon \rightarrow 0} \frac{\ln X_q(\varepsilon)}{\ln \varepsilon} \quad (4)$$

The ideal, regular multifractal curve, $\ln X_q(\varepsilon) - \ln \varepsilon$, satisfies the strict linear relationship, and actual series with multifractal characteristics also meets good linear relationship, otherwise, abnormality will occur as q value changes.

After performing Legendre transform of $\tau(q) - q$, we obtained

$$\alpha = \frac{d(\tau(q))}{dq} = \frac{d}{dq} \left(\lim_{\varepsilon \rightarrow 0} \frac{\ln X_q(\varepsilon)}{\ln \varepsilon} \right) \quad (5)$$

and

$$f(\alpha) = \alpha q - \tau(q) \quad (6)$$

The curve $\alpha - f(\alpha)$ composed of α and $f(\alpha)$ is the multifractal spectrum of the calculated series and reflects the unevenly distributed property within time series $\{x_i\}$. α denotes different signal subsets, among which, one represented by α_{\min} corresponds to large signals, while the one represented by α_{\max} corresponds to small signals. Hence, the width of multifractal spectrum, $\Delta\alpha = \alpha_{\max} - \alpha_{\min}$, can reflect the difference between both signals, α_{\max} and α_{\min} , and greater $\Delta\alpha$ means greater difference between both signals. The size of $f(\alpha)$ presents the frequency at which the signal subset of singularity α occurs in the entire loading process. Let $\Delta f = f(\alpha_{\max}) - f(\alpha_{\min})$, then, Δf reflects the relationship between small and large signal frequencies.

Although multifractal singular spectrum analysis reveals its singularity distribution, it does not take time into account. Thus, it is difficult to describe the dynamic evolution

process of instable and nonlinear system. To reveal spatiotemporal dynamic characteristics of multifractal system and instable random fractal signals, temporal multifractal spectra, or windowed multifractal singular spectra, are put forwarded (Wang and Zhu, 2001; Masao and Takehisa, 2007; Gang et al., 2012).

5 Let EMR time series be $\{y_i\}$, its total time length is T . In time window l_t , if the time interval for data acquisition is Δt , then the EMR time series X_m in the time window l_t is:

$$X_m = \left\{ x_i = y_i | y_{i=am\Delta t; (l_t+am\Delta t)} \right\}, m = 0, \dots, \frac{T - l_t}{a\Delta t} \quad (7)$$

10 where a is a positive integer reflecting the data renewal rate of time series in the time window l_t . Put X_m into Eqs. (1)–(7) to find the $f_m(\alpha) - \alpha$ multifractal singular spectrum set and its relevant parameters, while the dynamic fractal singularity index at the moment $T_m = l_t + \alpha m \Delta \alpha$ is

$$\alpha_m = \frac{d(\tau_m(q))}{dq} = \frac{d}{dq} \left(\lim_{\varepsilon \rightarrow 0} \frac{\ln X_q(\varepsilon)}{\ln \varepsilon} \right) \quad (8)$$

$$15 \quad f_m(\alpha) = \alpha_m q - \tau_m(q) \quad (9)$$

Dynamic changes in multifractal parameters can be used to reveal the differences in microscopic EM emission mechanisms at different stages of coal deformation and failure. $\Delta \alpha_m$ indicates the distributive non-uniformity of the studied object and can be used to reflect differences in microscopic EM emission mechanisms of loaded coal. Greater $\Delta \alpha_m$ indicates a greater difference among microscopic EM emission mechanisms. Δf_m is a measure of the ratio difference between the numbers of great and small events of the studied object and can be used to measure the proportion of strong and weak EM emission mechanisms. $\Delta f_m > 0$ means that weak EM emission mechanisms are dominant over the strong ones, while $\Delta f_m < 0$ indicates the strong ones are dominant.

25 For the spatial variation of the electromagnetic radiation during underground mining, $\Delta \alpha_m$ and Δf_m have clear physical meanings. The EMR released from coal or rock is

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a result of the combined action of different micro radiation mechanisms (Gokhberg et al., 1982; Nagahama and Teisseyre, 1998; Freund, 2004; Triantis et al., 2006; Miura and Nakayama, 2001; Muto, et al., 2006; Akito Tsutsumi et al., 2008). Generation of EM signals is related to the dislocation and sliding of coal joints, cracks, and lattices, as well as crack development and could lead to dynamic nonlinear changes ~~hang~~ of EMR. The greater the $\Delta\alpha_m$ is, the more obvious the multi-fractal characteristics of EMR, which suggests increased difference of EM mechanisms and implies coal and rock system from stable state into nonlinear acceleration deformation stage, reduced stability and increased outburst risk. Δf_m reflects the difference in proportion of micro mechanisms of EMR. EMR is associated with coal or rock dissipation energy (Yao et al., 2010; Song et al., 2012). The greater the dissipated energy rate is (the greater the damage rate is), the greater the EMR intensity. Thus, compared to the strong plastic flow (shear failure), brittle fracture (crack propagation) is a strong microcosmic mechanism of radiation. $\Delta f_m > 0$ indicates that the weak radiation mechanism is dominant and suggests that the coal and rock system is prone to plastic flow failure (sliding failure). $\Delta f_m < 0$ indicates that strong micro radiation mechanism is dominant and that the coal rock system is at the stage of crack propagation.

4.2 Time-varying response characteristics of EMR from coal rock burst

Figure 8 shows the temporal multifractal spectrum of EMR measured in the excavation of the bolted roadway of No. 23150 mining face of Coal Mine A. In the rock burst development, $\Delta\alpha_m$ gradually increased from 0.2 to 0.48. At the same time, Δf_m gradually increased from -0.9 to the maximum 0.38. After the peak, both $\Delta\alpha_m$ and Δf_m decreased and then maintained at a certain level, and Δf_m fluctuated around zero. During this period, the rock burst occurred.

During roadway excavation, the variations in multifractal EMR parameters, $\Delta\alpha_m$ and Δf_m , mainly underwent three phases: the embryonic, developmental, and critical phases. At the early excavation, the roadway ends were far from the stress concentrated areas. As shown in Fig. 8, $\Delta\alpha_m$ was between 0.2 and 0.28 and Δf_m was less

than 0 (−0.1 or so), this phase was called the embryonic phase. With the working face gradually approaching the stress concentrated area, the difference in EMR formation mechanisms increased, coal rock gradually entered the nonlinearly accelerated deformation phase, and the rate of crack extension enlarged, leading to enhanced coal rock plasticity, and making the coal rock system prone to shear sliding failure. At this time, $\Delta\alpha_m$ increased from 0.28 to 0.48, and Δf_m increased from −1.0 to the critical value 0, that is, the coal rock system entered the developmental phase. With the excavation roadway advancing, $\Delta\alpha_m$ reached its peak and began to decrease, and Δf_m fluctuated around the critical value 0 (from −0.5 to +0.48), that is, the coal rock system was in the critical phase. In this phase, the cracks developed sufficiently, the rate of their extension decreased to a certain extent; the coal rock system transmitted from the phase of cracks dominated damage into the phase of shear sliding-dominated damage. The system entered into organized critical state and formed the dissipative structure with certain stability; however it was prone to overall instability under external disturbances. The rock burst event occurring in the excavation of the bolted roadway of No. 23150 caving face was in this phase. After the rock burst, the energy concentrated in surrounding rock was released and the coal rock system anew entered the first phase of coal rock deformation, $\Delta\alpha_m$ and Δf_m returned to the initial level.

Figure 9 shows the temporal multifractal spectrum of EMR in the advancing face of Coal Mine B. This rock burst event occurred after the $\Delta\alpha_m$ reached its peak and Δf_m fluctuated around zero, which were similar to the rock burst occurred at the excavation roadway of Coal Mine A. Before this, both $\Delta\alpha_m$ and Δf_m increased gradually from 0.15 to 0.27 for $\Delta\alpha_m$ and from -0.6 to 0 for Δf_m , which can be considered as the developmental phase of rock burst. It was difficult to distinguish the embryonic phase from the developmental phase. In the embryonic phase, Δf_m also fluctuated around zero “fiercely”, but $\Delta\alpha_m$ kept at the low level (0.1–0.15). The in-situ analysis indicated that Coal Mine B was already in a broken state, and its crack development was more sufficient. So, characteristics of both elastic compaction and micro-crack nucleation stages of coal rock were not obvious. Under mining-induced stress, coal rock was

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prone to friction sliding failure, thus resulting in $\Delta f_m > 0$. Only when the instantaneously released elastic strain energy of surrounding rock is much larger than the friction sliding dissipated energy of coal rock, new fracture section can be formed; and at this time, $\Delta \alpha_m$ further increases, Δf_m is more often less than 0 (the developmental phase).

For non rock burst-prone area, the variation tendency of $\Delta \alpha_m$ and Δf_m is different from those in the rock burst-prone zone. $\Delta \alpha_m$ approximately equals 0.1 (simple fractal) and Δf_m fluctuates under 0 (see in Fig. 10). Experimental phenomena indicate that coal or rock is in a stable state for non rock burst-prone zone, and the mechanism of electromagnetic radiation is relatively single.

From the above typical examples, it is obvious that only when the variations in $\Delta \alpha_m$ and Δf_m are analyzed simultaneously, the phase and state in which the coal rock system stays can be determined. Before rock burst, the system must experience the embryonic, developmental, and critical phases, the temporal multifractal spectra of EMR released by coal rock staying in different phases are different, that is, they have their own independent characteristics.

5 Discussions

5.1 Nature of time-varying multifractal spectrum of EMR from coal rock bursts

Some scholars conducted a lot of experiments to study the microscopic EME mechanism and found that the generation of EMR is directly or indirectly related to mechanical processes, such as the piezoelectric effect (Nitsan, 1977; Ghomshei et al., 1989; Huang, 2002), the electrodynamic effect (Martelli et al. 1989), ~~crack opening and expansion caused electric charge separation and relaxation~~ (Ogawa et al., 1985; Enomoto, et al., 1990; Tzanis et al., 2000; Vallianatos et al., 2004; Rabinovitch et al., 2007), the variable motion of electric charges (Gokhberg et al., 1982; Nagahama and Teisseyre, 1998; Freund, 2004; Triantis et al., 2006), and the Coulomb field of the surface charges generated by the fractional sliding effect, etc. (Miura and Nakayama, 2001;

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Muto, et al., 2006; Akito Tsutsumi et al., 2008). It is clear that the damages caused by several different types of failure such as crack opening, crack propagation and fractional sliding can produce EMR, but their corresponding micro emission mechanisms are different. This difference is likely the principal reason causing the time-varying characteristics of EMR fractal and the dynamic changes in approximate entropy.

According to irreversible thermodynamics of damage evolution, Kawada (2007) introduced electric dipoles, explained theoretically the critical phenomena of EM emission and the time-scale invariance. Based on the law of energy conservation for the thermodynamic equilibrium system, in fact, he established a coupling model for the EMR field and mechanical energy release during coal damage evolution, namely:

$$dG = -sdT - \frac{\partial G}{\partial \sigma} d\sigma - \frac{\partial G}{\partial p} dp + \frac{\partial G}{\partial \alpha} d\alpha, \quad (10)$$

where G is the Gibbs free energy, s the entropy density (Nagahama and Teisseyre, 1998), T the absolute temperature, $\partial G / \partial \sigma$ the macroscopic elastic strain, $\partial G / \partial p$ the electromagnetic field (\tilde{E}). When damage evolution is an isothermal and linear irreversible process, and p are as follows:

$$\frac{d\alpha}{dt} = -\Gamma \frac{\partial G}{\partial \alpha}, \quad (11)$$

$$P = k\tilde{E}, \quad (12)$$

where Γ is the constant of an irreversible reaction process, k is the electric susceptibility.

Equation (12) is the coupling equation of the mechanical energy release rate and damage evolution. Thus the coupling model of EMR and the material damage evolution process is built by combining Eqs. (11)–(13). The above model is built based on the isothermal and linear irreversible thermodynamic process, as well as on the damage statistical mechanics which do not distinguish damage types. In fact, the dissipated energy in the material deformation and failure process is used up in the damage

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evolution process caused by irreversible internal variable, friction, sliding and thermal dissipation, therefore the above model has its limitations. Although it can well explain the critical phenomena of EM emission, it is difficult to explain its dynamic multi-fractal characteristics.

EM emission from coal or rock is closely relevant to the stress state. The stress determines the process of coal and rock damage evolution, thus affecting EMR dynamic changes. Some scholars have already revealed the relationship of coal electromagnetic radiation and damage evolution process. The rock damage evolution is related to the deformation and failure process of energy dissipation, and the damage evolution model could be established based on dissipative energy. Hence, EMR has intrinsic relationship with the dissipated energy, from the view of thermodynamic laws and damage mechanics and based on the types of coal deformation and failure, we introduce the damage internal variable, construct a coal and rock dissipation potential function and establish the coupling model between EMR and dissipation energy, which revealed the nature of dynamic nonlinear characteristics of EMR. Literature (Hu et al., 2013) gives the details of the modeling process.

Rock burst is a dissipative structure that can exchange matter and energy with the outside world (Lu et al., 2004, 2007). In fact, it is composed of coal and rock units that stay in different states, or in its implicit complexity (multi-scale features and fractal structures), which leads to the spatiotemporal multifractal of EMR. The rock burst system can be described by entropy flow and entropy change. In the early development phase of rock burst, the system is in a nearly equilibrium state. At this time entropy change is slightly smaller than entropy flow (the dissipation energy is less than the input energy from outside world), coal rock is in elastic deformation, compaction, and micro cracks nucleation stage, the emitted EMR is contributed mainly by micro crack nucleation, $\Delta\alpha_m$ maintained at a lower level, and Δf_m is mainly controlled by the first kind of microcosmic mechanism of radiation. When the mining space advances to the stress concentration area, entropy change starts to deviate from entropy flow (the external input energy suddenly increases, much larger than the capacity consumed by the

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system), crack expansion and penetration are accelerated, forming multiple fracture structure. At the same time, due to coal rock cracks induced damages, shear stress induced plasticity is enhanced, the shear slip failure mode gradually increases, resulting in multi-fractal dimensions and dynamic changes of EMR emission: $\Delta\alpha_m$ gradually increases, Δf_m changes gradually from one microscopic radiation mechanism (less than 0) to another micro-radiation mechanism (greater than 0). When the system is fully in the self-organized critical state, i.e. entropy change \approx entropy flow, the system is in dissipative structure with a certain degree of stability and could absorb the external input energy through self-adjusting. However, it is prone to dynamic disasters under external disturbances. At this point, cracks are sufficiently developed. EMR is controlled by two kinds of micro mechanisms of radiation, $\Delta\alpha_m$ maintains at a certain level, and Δf_m fluctuates around zero.

5.2 Significance of temporal multifractal spectrum of EMR from coal rock bursts

EMR has obvious trend before rock burst. Rock deformation and failure mainly go through three phases: nucleation of micro cracks, extension and rupture instability. EMR emanates from early onset destructing microcracks with 1–2 cm width (Frid et al., 2005) before large-scale fracture. Hence, recording high frequency EMR generated much earlier before collapse could yield a significant time advantage for early warning.

In the above typical examples, EMR emitted from coal rock revealed its inner abnormality and possibility of rock bursts in 1–2 days. However, EMR signals from these two rock burst evolution processes are obviously different. In Coal Mine A, basal EMR intensity in the advancing roadway was around 20 mV and rock burst occurred at the process of EMR intensity declining. By contrast, in Coal Mine B, basal EMR intensity in the combined mining face was 150 mV and rock burst occurred in the process of EMR intensity increasing. Thus, the rock burst event may occur in the process of both EMR increasing and declining. The complex nonlinear behavior of the rock burst system can not be explained by some traditional theories, which have their own shortcomings in EMR monitoring and early warning.

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In fact, coal rock system is composed of coal and rock units. A local failure of the system will not necessarily cause its global burst failure. EMR signals released from the coal rock system originate from the comprehensive interaction among its components. EMR signals released from the processes of different failure mechanisms of single and composite samples have greater differences, as shown in Fig. 11.

EMR intensity of coal rock during deformation and rupture increases to some extent, which is not obvious in combined rock samples. The overall EMR intensity is kept around 1000 aJ although its signal components become more abundant. For a single rock sample, the peak EMR intensity is close to 1000 aJ and changes obviously only during deformation and rupture. This characteristic can be used to predict coal rock deformation and failure. However, EMR from combined rock samples is more complex and can not be used alone to distinguish outburst from failure. Increasing evidences have shown that it is difficult to quantitatively describe seismic electromagnetic radiation (SEMR) phenomena by “linear” models using “averaged” parameters. Because coal rock system is highly heterogeneous (at all scales) and anisotropic, currently fractal-theoretic models are the best to describe it.

The effective solution to rock burst prediction and early warning is the use of nonlinear theories and methods to study the origination and development of rock burst and to establish corresponding prediction methods. The concept of “fractal” was presented by Mandelbrot to assess and model the irregular and complex patterns (Mandelbrot, 1982). In this paper, we proposed the time-varying multifractal spectrum distribution, which reveals the spatiotemporal dynamic characters of fractal systems. We analyzed the temporal multifractal spectra of EMR from two typical coal rock bursts in deep coal mining spaces. The results showed that although EMR signals from coal rocks at different mining faces have certain differences, they may be generated by same mechanism of rock bursts. According to the temporal response characteristics of EMR, the inception and development of rock bursts can be divided into inception stage, development stage and critical stage. At the inception stage, coal rocks undergo elastic compaction, micro-crack nucleation and extension. The EMR signals are mainly from microcrack

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extension and controlled by the first formation mechanism. In this period, $\Delta\alpha_m$ is small and Δf_m is mostly smaller than 0. At the development stage, cracks further develop, rapidly expand, connect to each others, and form multi-scale fractures, leading to increase in coal rock damage and plasticity and shear sliding failure. During this period, EMR are generated from multiple mechanisms and its intensity is controlled by crack extension and shear sliding. Thus, $\Delta\alpha_m$ and Δf_m increase gradually, but the latter is still less than 0. At the critical stage, the coal rock system is at fully self-organized, critical state, and gradually forms fractal structure at multi-scales. During this period, $\Delta\alpha_m$ decreases slightly, Δf_m fluctuates around zero, and the system is prone to burst failure induced by external disturbances. At this time, an early warning should be issued. Overall, temporal response characteristics of EMR to imminent coal or rock dynamic disasters such as rock burst or roof caving, etc. at the underground mining space provide a reliable basis to issue an early warning.

6 Conclusions

EMR signals generated during underground mining as the fingerprint information of coal rock burst failure are closely related to microcracks nucleation (1–2 cm) and expansion of coal rock, and more closely to the inception and evolution of rock bursts. Coal rock in the hazardous zone exchanges matter and energy with the external world, and gradually evolves from a stable or equilibrium state to a non-equilibrium dissipative state, and eventually into a self-organized, critical state. EMR generation at mining face is mainly dominated by two types of microscopic mechanisms. The first one is the transient changes in stress-induced electric dipoles and electric charges due to crack-developing induced-variable motion, separation and relaxation (Gokhberg et al., 1982; Nagahama and Teisseyre, 1998; Freund, 2004; Triantis et al., 2006). The second is coulomb field due to accumulation dislocation, sliding and friction of electric charges on the fracture surfaces (Miura and Nakayama, 2001; Muto et al., 2006; Akito et al., 2008). EMR signal generation is related to the dislocation and sliding of coal joints, cracks,

and lattices, as well as crack development. For coal rock system at different states, the contributions of these two mechanisms are different, resulting in nonlinear, dynamic change in EMR.

Influenced by mining stress and excavation, coal rock system will spatiotemporally form multi-scale features and fractal structures, which in turn lead to emission of EMR with temporal multifractal features. The temporal multifractal spectrum of EMR intrinsically carries both spatial factor (multiple fracturing of coal rock) and temporal factor (the dynamic, temporal evolution of fractures). Therefore, it can accurately respond to deformation, rupture and failure and be used to monitor and early warn coal rock dynamic hazards.

Temporal response characteristics of EMR show that the process of coal rock burst evolution involve inception, development and critical stages. At the inception stage, coal rock undergoes elastic compaction and micro-crack nucleation. Thus, radiated EMR signals are contributed mainly by micro crack extension, meaning $\Delta\alpha_m$ is small and Δf_m is mostly less than zero. At the development stage, cracks rapidly expand, connect to each other and form multi-scale fissures, which further damage coal rocks and accelerate plasticity and shear sliding failure. During this period, the measured EMR signals are contributed mainly by crack extension and shear sliding and $\Delta\alpha_m$ and Δf_m increase gradually. At the critical stage, coal rock system steps into the self-organized, critical state, $\Delta\alpha_m$ decreases slightly and Δf_m fluctuates around zero, the system is prone to burst failure due to disturbances.

Although dynamic multi-fractal spectrum of EMR is an objective response to deformation and failure of the loaded coal rock and can be used to evaluate the deformation and fracture process and failure of coal rocks. However, the fractal parameters $\Delta\alpha_m$ and Δf_m of EMR are affected by various factors, including loading rate as well as the mechanical properties and stress levels of coal rock. Therefore, the dynamic changes in the multifractal parameters $\Delta\alpha_m$ and Δf_m and their impacting factors need to be further investigated.

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**Fig. 1.** KBD7 EMR monitoring instrument.

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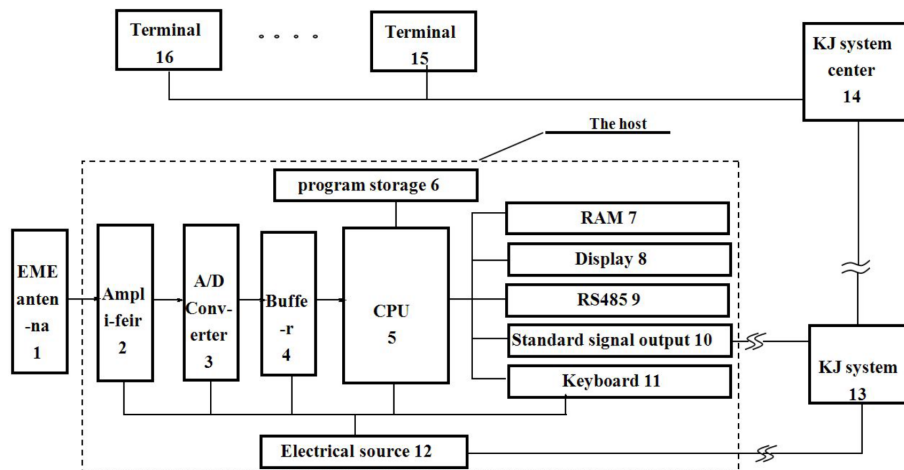


Fig. 2. KBD7 Coal and rock dynamic disasters non-contact EMR monitor principle diagram.

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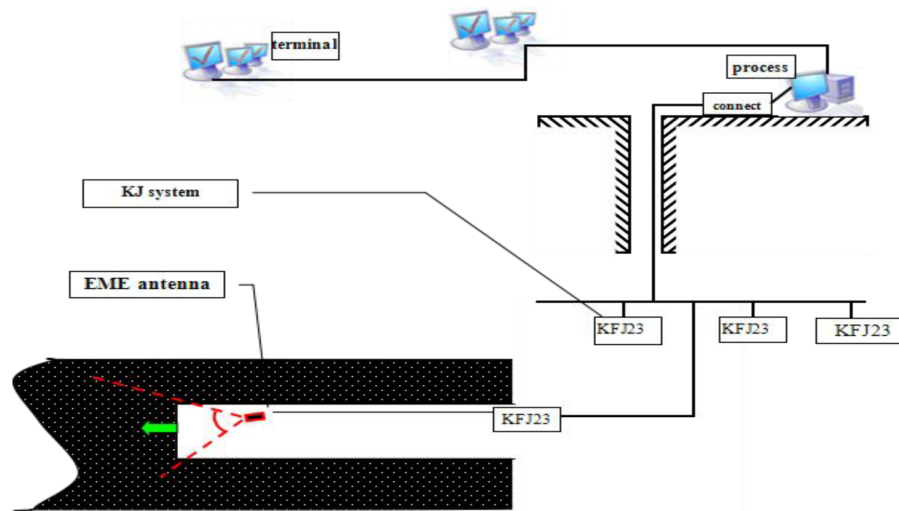


Fig. 3. Instrumentation arrangement of the KBD7 EMR monitor system.

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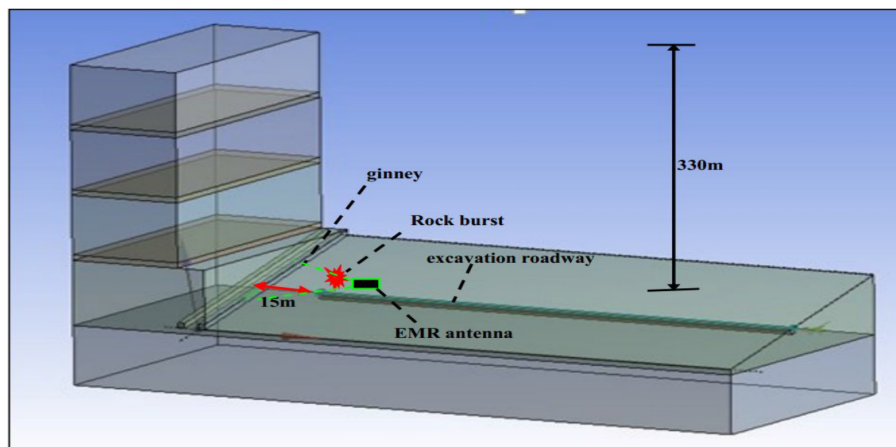


Fig. 4. Schematic of EMR monitoring in the mining roadway.

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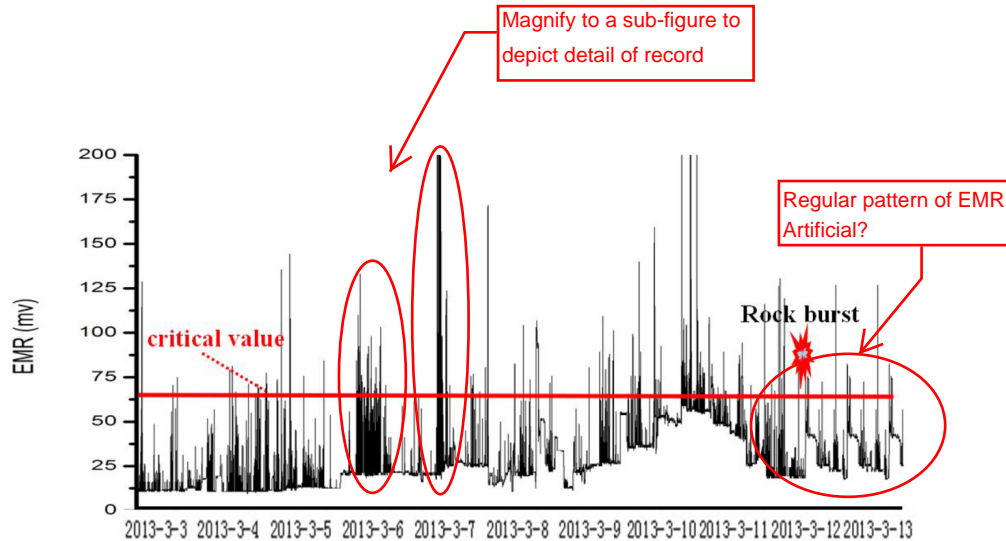


Fig. 5. Dynamic variation of EMR from coal rock at the mining roadway of Coal Mine A before and after the rock burst occurred before dawn on 12 March 2013.

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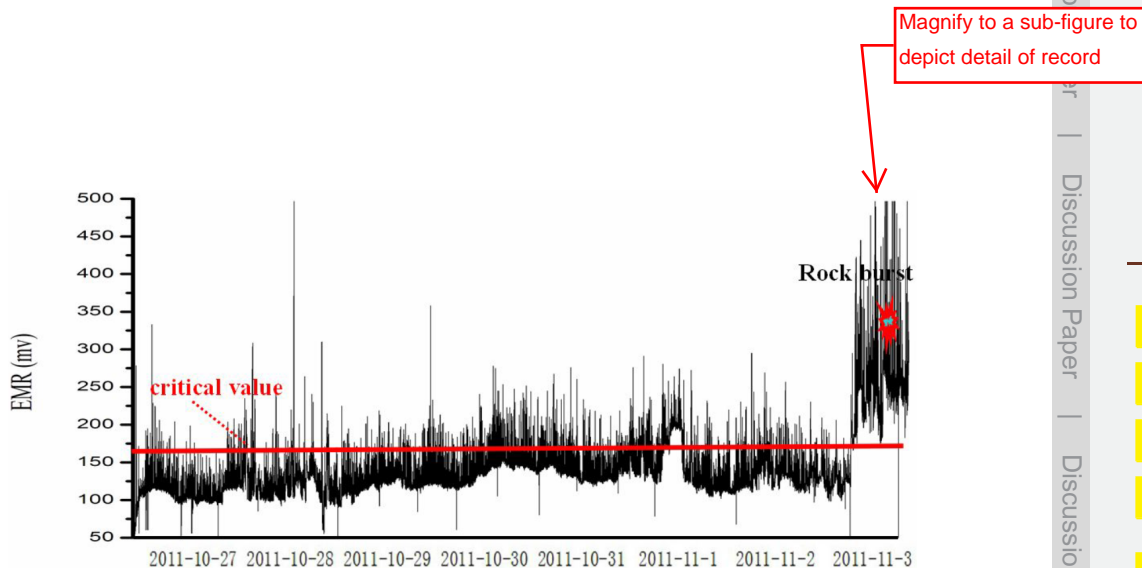


Fig. 6. Dynamic variation of EMR generated from the coal rock of the bolted roadway of Coal Mine B before and after rock burst at 19:45 LT on 3 November 2011.

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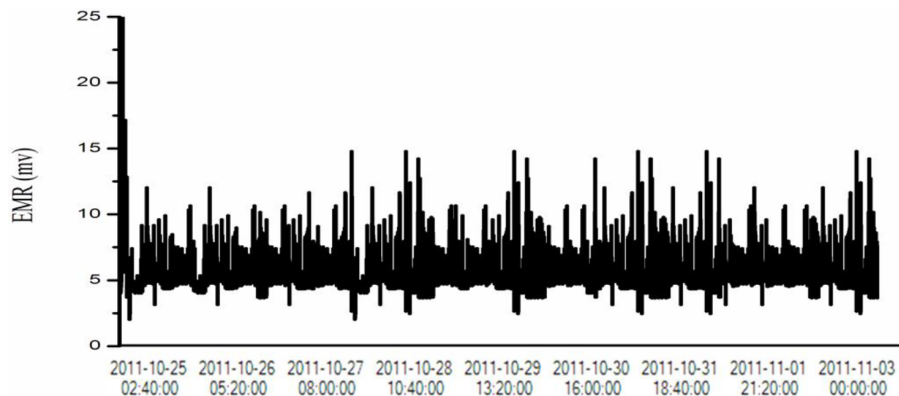


Fig. 7. Dynamic variation of EMR generated from regions that no damages were developed.

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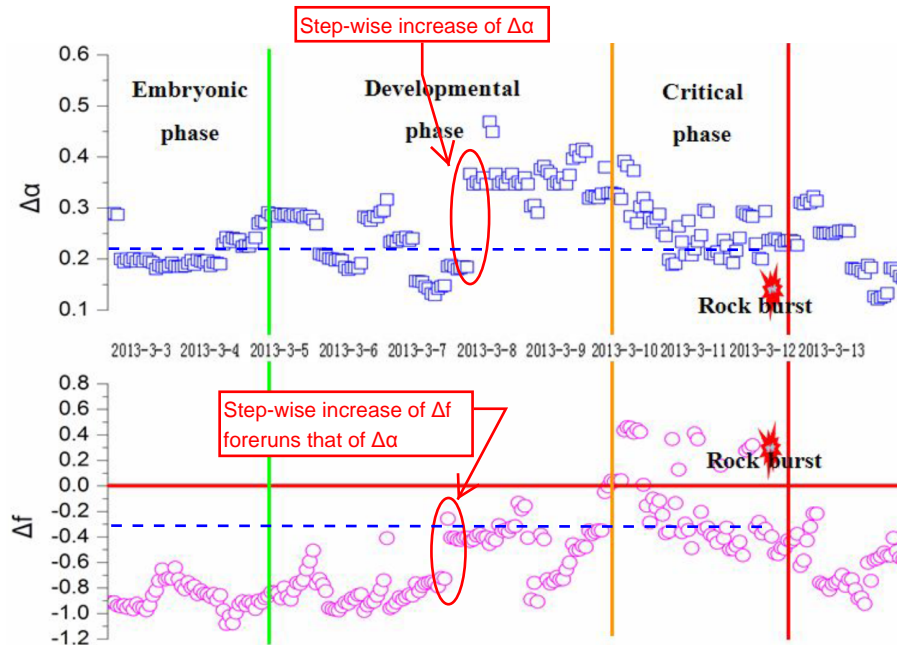


Fig. 8. Temporal multifractal spectrum of EMR in No. 23150 roadway of Coal Mine A.

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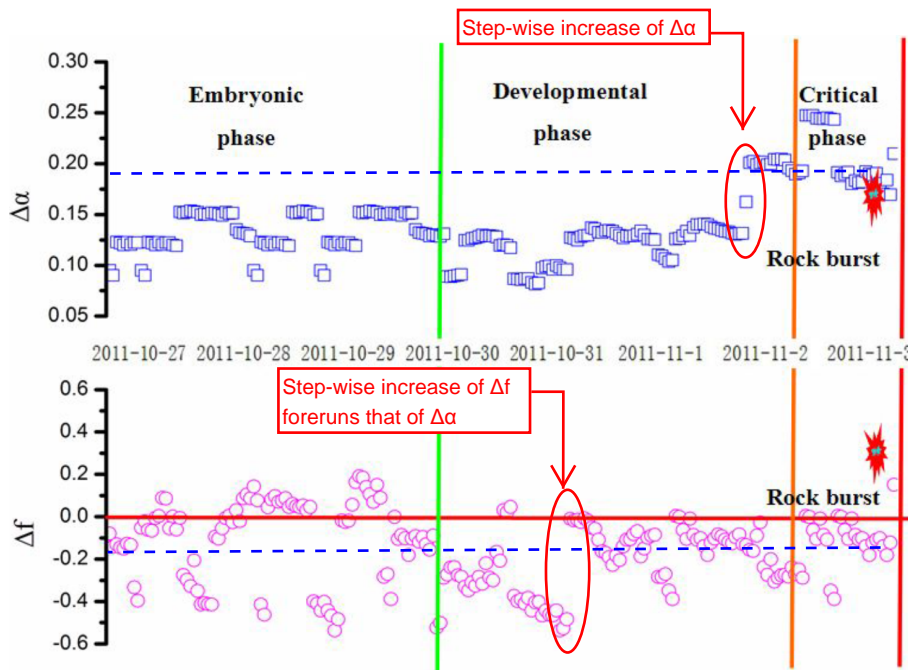


Fig. 9. Temporal multifractal spectrum of EMR in the bolted roadway of heading face of Coal Mine B.

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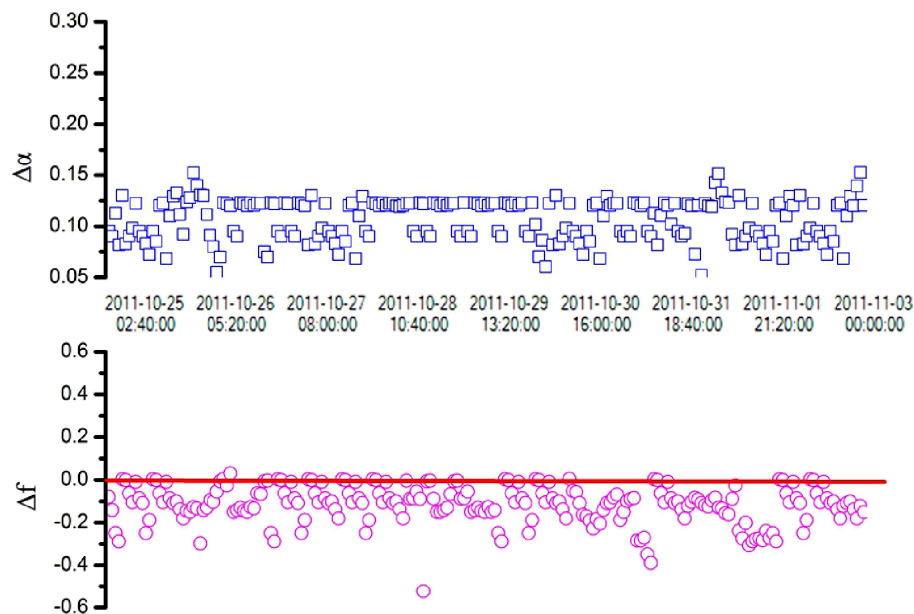


Fig. 10. Temporal multifractal spectrum of EMR in non danger zone.

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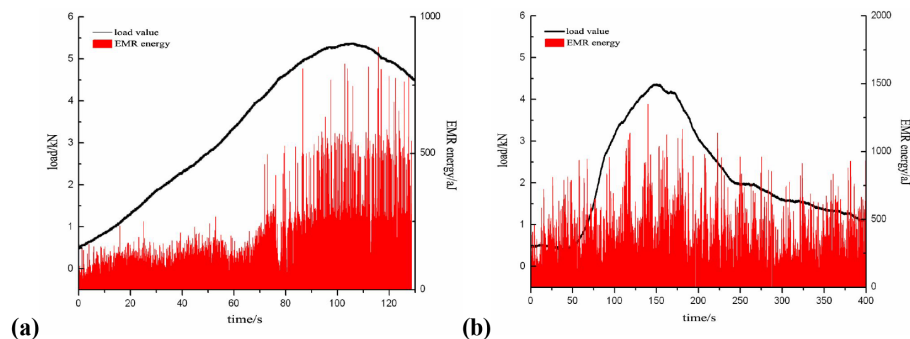


Fig. 11. Changes in EMR from the coal rock unit and their combination. **(a)** EMR from a coal rock unit at loading rate of 0.1 mm min^{-1} ; **(b)** EMR from complex coal rock compose of four coal and rock units at loading rate of 0.1 mm min^{-1} .

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