A new algorithm for calculating ventilation network reliability based on truncation error theory and network simplification

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Abstract

Study of reliability algorithms for large-scale and complicated ventilation networks is one of the hotspot research areas in this field both at home and abroad. At present, there is too much operand caused by combination explosion in determining ventilation network reliability; computing network reliability by using disjoint principle is one of the most efficient methods but it can not quickly determine the reliability of large-scale networks. Considering this problem, we adopt a new method of direct constructing disjoint paths, at the same time, combine the truncation error theory with network simplification technology, and propose a new algorithm for determining the reliabilities of large-scale ventilation networks. The application effect of ESR is perfect. The reliability of the ventilation network (with 189 branches) of NO.2 mine area of Jinchuan Company can be determined in 24 second by ESR algorithm provided in the paper, so the problem that can not be solved in 10 hours is solved in the paper.

Keywords: Ventilation network; Reliability; Network simplification; Truncation error

1. Introduction

According to the state safety production development plan (2004-2010), to enhance the optimal technologies for the anti-disaster ability and reliability of mine ventilation system and airflow control technologies during disaster period is one of preferential developing research areas in great safety science and technology. In 2008, State Administration of Work Safety put forward a new work system for mine safety, i.e. “reliability in ventilation, reaching standard in gas drainage and mining, efficiency in monitoring, management in place”. In the system, reliability in ventilation is determined as the primal content in mine disaster prevention and control work, which scientifically reflects the fundamental function of ventilation in mine disaster prevention and control.

In the study of ventilation system reliability, the quick determination algorithm of large-scale and complicated ventilation system is one of the hotspot research areas at home and abroad.

According to traditional methods, the reliability of a ventilation system at time $t$ can be computed by using formula (1) [1-3].

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\[
R_{t}(t) = \sum_{L \in \mathcal{L}} R(L, t) \sum_{j \in M} R(L, t) + \sum_{j \in M} R(L, t) + \cdots + (-1)^{t-1} \prod_{i \in \cup r} R(L, t)
\]

(1)

Where \(P_i\) is the path in a ventilation system; \(w\) the independent path number, \(w=n-m+2\); and \(R(L, t)\) the reliability of branch \(L\) at time \(t\).

The combination of any \(k\) paths is used in the above calculation \((k=1,2,\ldots,w)\). As the number of such combination is great, combination explosion occurs, which shows that it is impossible to compute reliability by using formula (1), so many simplified calculating methods based on formula (1) occur at home and abroad.

Aiming at the problem of excessive computation in determining network reliability, based on the analysis of the current methods in literatures [4-7], ESR algorithm which fits to determine the reliability of a large-scale ventilation system is put forward [8], namely “the algorithm for computing ventilation network reliability based on truncation error theory and network simplification technology”. The reliability of the ventilation system (189 branches) of NO.2 mine area of Jinchuan Company is determined in 24 min by using the algorithm, and the problem which can not be solved by methods in literature [4-7] is solved.

2. To construct disjoint path set directly

At present, there are 2 methods to construct disjoint path set, namely direct method and indirect method, and direct method is adopted in the paper. The reliability of a ventilation system can be computed by formula (2) after the disjoint path set is determined.

\[
R_{net} = \sum_{i=1}^{s_p} \prod_{j=1}^{|P[j]|} R(e(j)), (e(j) \in P[i])
\]

(2)

Where, \(S_p\) is the number of disjoint path set; \(P[i]\) the disjoint path \(i\).

If the node set of a ventilation network is \(V = \{v_1, v_2, \ldots, v_n\}\), and the branch set is \(E = \{e_1, e_2, \ldots, e_m\}\). Then a multi-source or multi-sink network can be converted to a single-source and single-sink network by adding virtual branches and virtual nodes.

To discuss expediently, the converted network is noted as \(G\), and the source is noted as \(v_1\), sink is noted as \(v_n\).

Every node has an information element set \(IS[i]\), whose element can be expressed as \(M \in \{1, e_i, \overline{e_i}\}\). We stipulate \(1e_i = e_i, 1 = e_i\). The algorithm (algorithm 1) step can be showed as follows [7]:

1. Initialization. Let \(IS[i] = \Phi, v_1 \in V, v_1 \neq v_1, \) and \(IS[1] = \{1\}\);
2. \(\forall v_i \in V, v_i \neq v_i, \forall M \in IS[i]\). The branches in \(E^-(v_i)\) are scanned as the intended order which can be determined in advance;
   1. To determine the out branch set of \(M\) to \(E^+(v_i)\). To branch \(e\) in \(E^+(v_i)\), if there is a item \(e \in E^+(v_i)\) in \(M\) or there is a item which is equal to \(e\), \(e\) is not a branch of the out branch set, or \(e\) is a branch of the out branch set;
   2. To the first branch \(e_1\) in the out branch set, the information \(Me_1\) is sent to the other node of \(e_1\), namely \(Me_1\) is an element of the \(IS\) of the other node of \(e_1\). To the second branch \(e_2\) in the out branch set, the information \(Me_2\) is sent to the other node of \(e_2\), namely \(Me_2\) is an element of the \(IS\) of the other node of \(e_2\), if there are \(t\) out branches, \(t\) such operations will be carried out;
   3. If \(e_k\) is the first branch without underline in \(IS[i]\) from right to left, the information \(\overline{Me_1e_2\cdots e_t}\) will be sent to the other node of \(e_k\);
   4. \(M\) can be removed from \(IS[i]\) after the above operations to \(M\) are done. \(M\) can be removed directly from \(IS[i]\) if there is no out branch for \(M\);
3. To repeat (2) until \(IS[i] = \Phi\) for every \(v_i \in V\);
(4) The final disjoint minimum path set of the ventilation network is the $IS[m]$ of $v_m$.

To large-scale networks, algorithm 1 is also too slow, and the reliability of NO.2 mine area of Jinchuan Company cannot be determined in 10 hours by algorithm 1. Aiming to this phenomenon, ESR algorithm for computing the reliability of a large-scale ventilation network is put forward.

3. Principle of ESR algorithm

ESR algorithm is put forward based on two principles, namely truncation error and network simplification.

Considering ② and ③ in the step (2) of algorithm 1. $M\overline{e_1e_2\cdots e_t}$ is sent to the other node of every node, so the sent character string (the character expression of an event) will be longer and longer with the development of the process. The reliability of branch $i \Rightarrow R[i] \leq 1.0$. The corresponding reliability of the sent character string is equal to the continued product of the corresponding reliability of every element in the character string, so the corresponding reliability of the sent character string will be smaller and smaller with the increase of the sent character string, so that the value can be neglected when it is small enough. If the corresponding reliability of the character string is less than or equal to $10^{-4}$, the character string can be block, namely the forward spread and backward spread of the character string will be terminated. These block operations will be more than one time, so the truncation error may accumulate to a certain extent [10]. Iterative method is adopted, the computing results approach the true value with the increase of $\lambda$. The iterative process will be terminated if the difference of two neighbor iterative results is less than the given precision $\varepsilon$.

The disjoint path based reliability computing algorithm is based on paths. If there are parallel branches in a ventilation network, the path number will increase manifold. The number of disjoint paths is much larger than the number of paths, so it is essential to replace parallel branches with an equivalent branch when the reliability of a ventilation network is being computed. The computing time is shortened sharply and the memory usage is reduced by using the above treating methods. The simplification of serial sub-networks has no effect on path number. The computation of diagonal sub-networks is also huge, so only parallel sub-networks are simplified in ESR algorithm so as to maximize the computing speed.

4. ESR algorithm

ESR algorithm put forward in the paper can be expressed as follows.

(1) To do pretreatment, namely to convert a multi-source or multi-sink network to a single-source and single-sink network, and to determine the out branch set $E^-(v_i)$ of every node;

(2) To do network simplification. In order to enhance computing speed, only parallel sub-networks are simplified in a large-scale network, and to determine the reliability of the equivalent branches;

3) Let iterative number $k = 1$, iterative precision index $\lambda = 5 \times 10^{-4}$;

(4) Let $IS[1] = \Phi$, $v_i \in V, v_i \neq v_s$, and $IS[1] = \{1\}$;

(5) $\forall v_i \in V, v_s \neq v_i$, $\forall M \in IS[i]$. The branches in $E^-(v_i)$ are scanned as the intended order which can be determined in advance;

① To determine the out branch set of $M$ to $E^-(v_i)$. To branch $e$ in $E^-(v_i)$, if there is a item $e \in E^-(v_i)$ in $M$ or there is a item which is equal to $\overline{e}$, $e$ is not a branch of the out branch set, or $e$ is a branch of the out branch set;

② To the first branch $e_1$ in the out branch set, the information $Me_1$ is sent to the other node of $e_1$, namely $Me_1$ is an element of the $IS$ of the other node of $e_1$. To the second branch $e_2$ in the out branch set, the information $Me_1e_2$ is sent to the other node of $e_2$, namely $Me_1e_2$ is a element of the $IS$ of the other node of $e_2$, ......, if there are $t$ out branches, $t$ such operations will be carried out;

③ If $e_t$ is the first branch without underline in $IS[i]$ from right to left, the information $Me_1e_2\cdots e_t$ will be sent to the other node of $e_t$;

④ $M$ can be removed from $IS[i]$ after the above operations to $M$ are done. $M$ can be removed directly from $IS[i]$ if there is no out branch for $M$;
(6) To repeat step (5) until \( IS[i] = \emptyset \) for every \( v_i \in V \);

(7) The final disjoint minimum path set of the ventilation network is the \( IS[m] \) of \( v_i \);

(8) to compute the reliability of the ventilation network \( R_{\text{net}}^k \) in the \( k \)-th iteration according to formula (2).

(9) If \( k > 1 \) and \( |R_{\text{net}}^k - R_{\text{net}}^{k-1}| < \epsilon \), turn to step (10), otherwise let \( k = k + 1 \) and then turn to step (4);

(10) End. The reliability of the ventilation network is the result in the \( k \)-th iteration, namely \( R_{\text{net}} = R_{\text{net}}^k \).

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(1) Network simplification is used in reliability computation, and hence the number of disjoint paths is reduced effectively. Truncation error theory is used in reliability computation, and hence computing time is reduced greatly on the premise of enough precision.

(2) The new algorithm for computing reliability based on truncation error theory and network simplification technology put forward in the paper adapts to all kinds of network, especially adapts to large-scale network.

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