DOI: 10.1051/e3sconf/20172503008

Increase the reliability of operation of differential protection due to the use of the method of double entry

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Abstract. Double entry it is method of registration of economic operations accounting, applied to detect errors. The application of the method in differential protection leads to increased reliability of technical solutions. By providing redundant processing of information about currents measured at the ends of the protected object, and is formed in a special matrix that implements the reliable operation of the differential protection, eliminating its excessive action when damaged the current transformers or communication lines. To assess the reliability of protection used the method of Markov chains. The obtained results allow to make a conclusion about the prospects of implementing a differential protection using the method of double entry in the electrical networks.

1 Introduction

One of the promising directions of development of system of relay protection (SRP) is the establishment of the centralized differential protection (CDP). Typical examples of the organization of the CDP are method of differential rings [1], which used in the ship power systems 13,8/4,16/0,48 kV and method of multi-zone differential protection [2]. Also has practical experience multiterminal line differential protection, which is a special case of CDP [3].

Consider the principles of operation protection on the example of the part of the 110 kV network.

In accordance with the method of differential rings, the network is divided into several regions (fig.1)

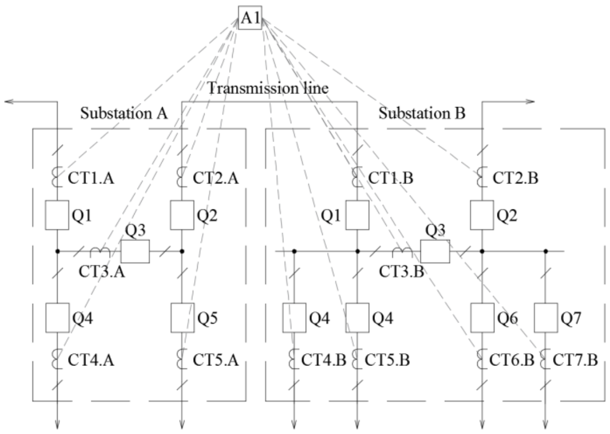

Fig. 1. Method of differential rings.

Region is formed by current transformers (CT) on the boundary of the protected area, is checked for fault in the network (region bounded by CT1.A, CT2.B, CT4.A, CT5.A, CT4.B, CT5.B). In case of detection fault, starts checking of differential protection of individual installations, and if fault is detected, isolates damaged item. Also in the process of functioning of protection there is a permanently diagnosis CT fault by checking on the presence of fault regions formed by the expanding of the zones of differential protection of installations to the next CT on both ends of the protected object.

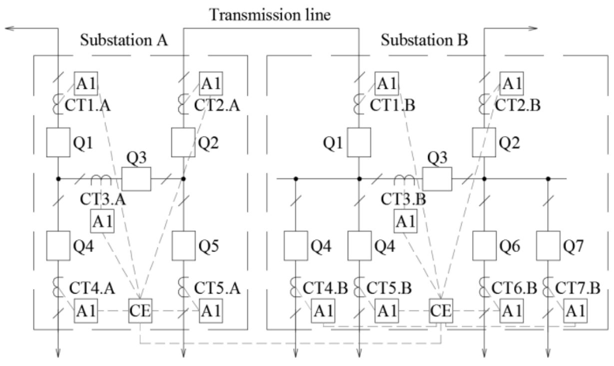

Fig. 2. Method of multi-zone current differential protection
A1- terminal; CE - central equipment; Q1-Q7- circuit breakers; CT1- CT7 - current transformers.

When using the method of multi-zone differential protection (fig. 2), terminals collect the measured values of currents and status of circuit breakers (CB). Established local central equipments (CE) collect data from the terminals on their own and adjacent substations. Once the local CE obtains all data required for the CDP, it will make the protection decision (trip or block) and transfer commands to the local CE of the adjacent substation.

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When CT fault is detected, protection zone will be extended to bigger due to the use of the data received from next CT.

A common disadvantage of the proposed approaches, from the point of view of the operation of modern electrical networks with changing configurations is the difficulty of the technical implementation.

The purpose of research is the development of highly reliable CDP with adaptation to the changes in the configuration of the electrical network. This problem is important in power systems with distributed generation, where the protection must react to dynamically changing network operation condition. Developed CDP may be applied both as main and as a backup.

2 Realization of proposed protection

CDP, proposed by the authors, based on the differential principle, in combination with the method of double entry [4]. Double entry - registration method of economic operations accounting, under which every change of the state funds recorded in two accounts, ensuring the overall balance.

When implementing the new CDP apply graph theory and the theory of matrices.

To illustrate the operation of protection, consider the part of the electrical distribution network shown in fig. 3a

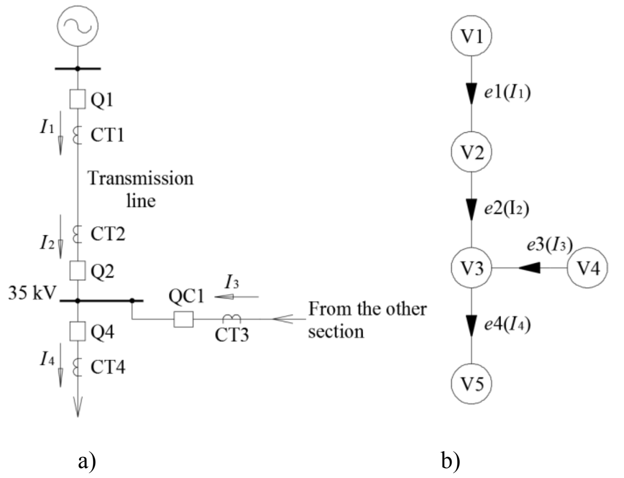

Fig. 3. Scheme of fragment of distribution network and an unidirectional graph.

The structure of the scheme displayed as a unidirectional graph (fig. 3b) with arcs representing the high-voltage units and the vertices representing the protected items – busbar and transmission line. Then, each vertex of the graph is represented by the special matrix of currents whose rows represent the vertices of the graph, the columns - the separation of arcs connecting the vertex on the directed to it and directed away from it.

For the present example, the matrix of currents will have the view:

$$MV1=\begin{bmatrix}0&0\\0&I_1\\0&0\\0&0\\0&0\end{bmatrix}\quad MV2=\begin{bmatrix}I_1&0\\0&0\\0&I_2\\0&0\\0&0\end{bmatrix}\quad MV3=\begin{bmatrix}0&0\\I_2&0\\0&0\\I_3&0\\0&I_4\end{bmatrix}$$

$$MV4=\begin{bmatrix}0&0\\0&0\\0&I_3\\0&0\\0&0\end{bmatrix}\quad MV5=\begin{bmatrix}0&0\\0&0\\I_4&0\\0&0\\0&0\end{bmatrix}$$

For determining the location of fault, protection compares the currents on differential principle for particular regions and detects potentially damaged item. For all graph vertices with degree >1 compile equations in matrix form for the sum of the currents at the nodes.

Then it is determined whether to trigger starting on fault in the region, or there is a CT or communication lines (CL) fault. The presence of a fault is determined using the method of double entry. Since each arc of the graph is reflected with the same weight (current value) in the matrices twice: as an arc, associated with the vertex directed to one matrix, and as the arc associated with the vertex directed from another matrix, in the case getting wrong values is the sum of incoming and outgoing currents in the two matrices becomes incorrect, but the total differential current of the whole network remains equal to zero. In case of observance of rule of detection of the fault and maintaining a sum of currents for the entire network is equal to zero, a CT or CL fault is detected.

Signs of the functioning of the differential protection for different ratios of currents and the results of performing matrix operations for this scheme is shown in Table 1.

Table 1. Results matrix operations and signs of the functioning of the protection.

The resulting value matrix operations			Signs of the functioning of the differential protection
SMV2	*SMV3*	*SUM*	
0	0	0	Fault is missing, CTs is functioning
≠0	0	≠0	Fault on the element, corresponding to vertex V2
0	≠0	≠0	Fault on the element, corresponding to vertex V3
≠0	≠0	0	CT Fault on CT, common to V2 and V3 (arc $e2(I_2)$)

In table 1 variables *SMV*2, *SMV*3, have been received by the resulting matrix operations, define the conditions of the existence of a fault in the protection zone. Variable *SUM* defines total differential current of the network.

Detection of CT fault of separate fider can be implemented by additional technical diagnostics or

DOI: 10.1051/e3sconf/20172503008

automatically by forming the resultant currents that characterize them operability. For example, by adding additional conditions to those shown in table 1 presents the additional matrices currents.

For example, for considered scheme, assuming that the feeder of circuit breaker Q4 represents the connection of power transformer, for inclusion in the protection zone of the CDP, need to connect the windings of CT of the transformer to the protection. In accordance with the principle of the protection, transformer representing an additional matrix *MV*6. Accordingly, changing in the structure of scheme will changes the dimensions of all matrices with 5x2 to 6x2 and a description of the matrix MV5, the degree of which is equal to 2.

The advantage of the proposed CDP is the flexibility of the system of the protection when changing network configuration due to the fact that the resulting matrices are generated automatically, in contrast to the protections discussed above, where for each network configuration, you must set special algorithms. Depending on the ratio of currents on the part of electrical network and results of operations on matrices of currents can be realized the reliable operation of the centralized differential protection network. This provides not only the action of protection in case of fault on each region, but excluded its excessive action when CT or CL faults.

3 Quantitative assessment of the reliability of the proposed protection

To quantify the advantages of the proposed technical solutions from the point of view of reliability, using the method of Markov chains. This method is often used to describe the processes of failure and repair with the elementary streams, and is most suitable for calculating reliability of SRP [5-8]. In this paper applies the mathematical model of the functioning of the SRP, presented in [6]. The distribution laws of failure and repair will accept exponential.

Taking into account specificity of the analyzed differential protection, define two types of protection failures:

- undesired-tripping protection failures (in the absence of fault on the protected object);
- fail-to-operate protection failures (in case of fault on the protected object).

This approach is used in several papers, e.g. [9].

In fig. 4 presents three variants of organization SRP: differential line protection (DLP) and differential busbar protection (DBP); CDP as a busbar protection and as a line protection; total system, consisting of distributed DLP, DBP and CDP, giving a signal, blocking the work of the DLP and DBP upon the occurrence CT or CL fault. Calculate reliability indices for all three cases on the basis [6, 10], and information from the manufacturers of relay protection.

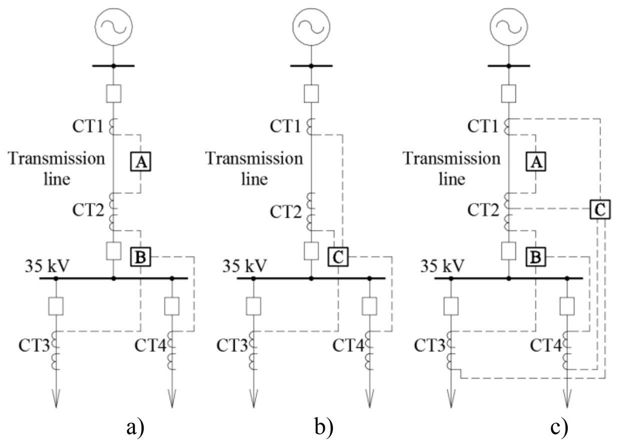

Fig. 4. Part of a network with connection of protections to CT a) the system includes a DLP (A) and DBP (B), b) SRP based on the CDP (C), c) SRP with the use of CDP (C) and distributed protection DLP (A) and DBP (B).

3.1 Mode 1: absence of fault on the protected object

In fig. 5 shows graphs of states and transitions in an absence of fault on the protected object mode. Here: Ew – state SRP without failures; A_1, B_1, C_1, $CT1_1$... $CT4_1$ – the state of the SRP in the presence of defects that could lead to undesired-tripping protection failures of devices of relay protection A, B or C, and, as a result, failure of the SRP in general; μ_1, μ_2 – repair rates of the relay protection and CT.

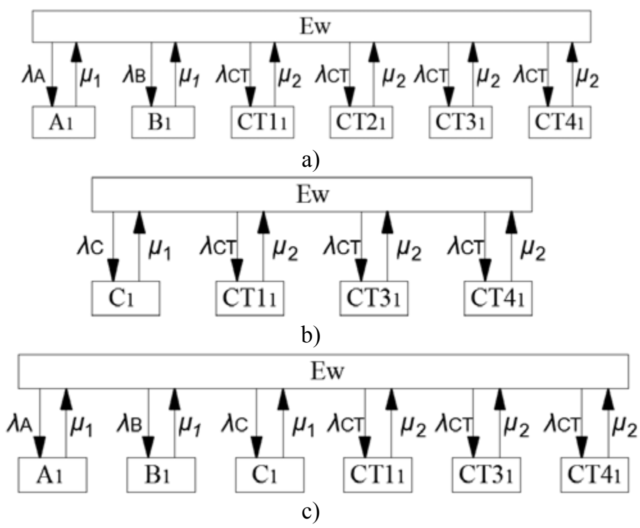

Fig. 5. Graphs of states and transitions for an absence of fault on the protected object mode a) the system includes a DLP and DBP, b) SRP based on the CDP, c) SRP with the use of CDP and distributed protection DLP and DBP.

Convert the graphs (fig. 5) to the form shown in fig. 6, where E_1 - failure state of SRP, λ_1 – the resulting failure rate of protection.

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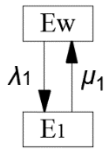


Fig. 6. Converted graph of states and transitions for an absence of fault on the protected.

Define the probability $P_1(t)$ that the system is in state E_1, which is an emergency, for random time *t*. Form a system of differential equations describing a graph, where $P_w(t)$ - the probability of location the system in state without failures E_w.

$$\left.\begin{aligned} \frac{dP_w(t)}{dt} &= -\lambda_1 \cdot P_w(t) + P_1(t) \cdot \mu_1 \\ \frac{dP_1(t)}{dt} &= \lambda_1 \cdot P_w(t) - P_1(t) \cdot \mu_1 \end{aligned}\right\} \quad (1)$$

Normalizing expression, the meaning of which is that the researched system located in state E_1 or E_w as constituting a complete group of events, has the form

$$P_w(t) + P_1(t) = 1$$

As at the initial moment of operation of the system at $t = 0$ the system is in state without failures:

$$P_w(0) = 1,\ P_1(0) = 0$$

As a result of solve the system of differential equations a function of the unreadiness probability

$$q(t) = P_1(t) = \frac{\lambda_1}{\lambda_1 + \mu_1} \cdot (1 - \exp[-(\lambda_1 + \mu_1)t])$$

Make an assessment of the probability of failure-free operation of the SRP. Probability of failure-free operation - is the probability that within a given work or a given time interval, the failure of the object does not occur [6].The graph for the calculation will look similar as the graph in fig. 6 with the difference that it will not be possible to transition from state E_1 to E_w, that is excludes repair rate μ_1. This circumstance is due to the fact that when system fails (transition to absorbing state E_1), the experiment is finished – the system cannot leave this state.

Due to absence of repair instead of a system of differential equations (1), the result will be an expression of the probability of failure-free operation (PFFO), with exponential distribution law:

$$R(t) = P_w(t) = \exp[-(\lambda_1 \cdot t)] \quad (2)$$

In fig. 7 shown the dependences of the function of the unreadiness probability of SRP, and functions of the PFFO on the average time between checks.

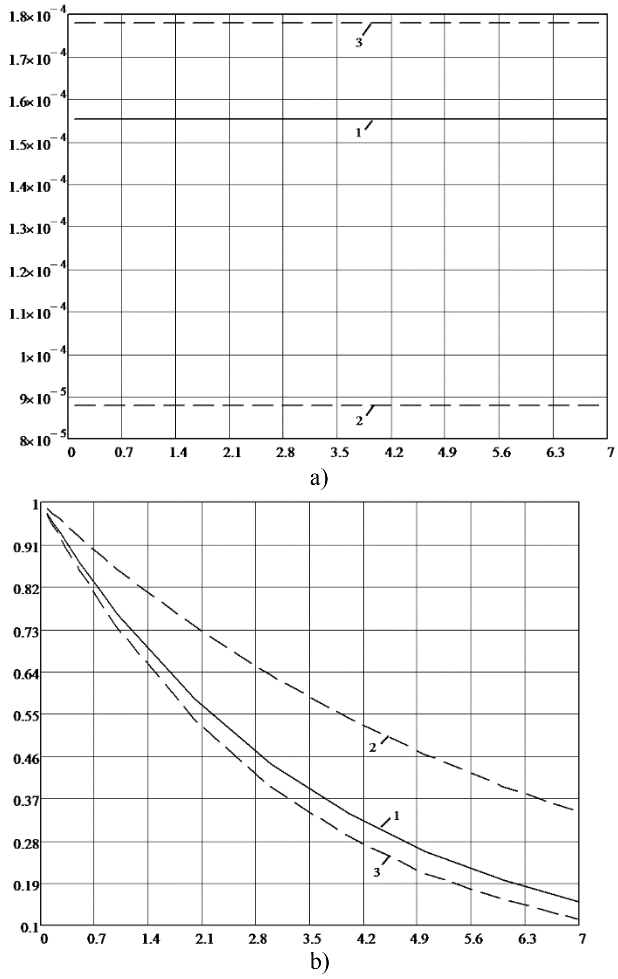
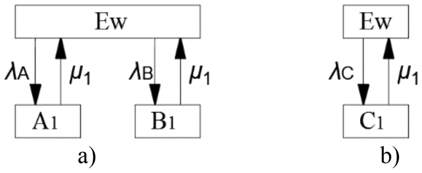


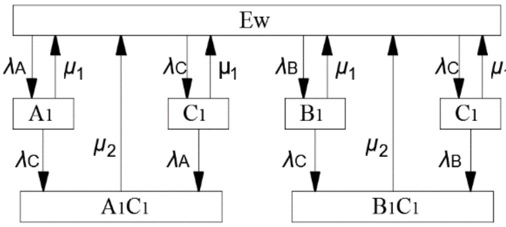
Fig. 7. Function of the unreadiness of SRP (a) and function PFFO of SRP (b). 1 - the system includes a DLP and DBP; 2 - SRP based on the CDP; 3 - SRP with the use of CDP and distributed protection DLP and DBP.

The analysis of graphs in fig. 7a shows that the functions of unreadiness probability are straight lines, the values of which are close to zero. This is due to the fact that for the considered case, the repair process can be considered instantaneous.

3.2 Mode 2: in case of fault on the protected object

In fig. 8 shows graphs of states and transitions in case of fault on the protected object mode. Here: E_w – state SRP without failures; A_1, B_1, C_1 - the states of the SRP in the presence of defects that could lead to fail-to-operate protection failures of devices of relay protection; A_1C_1, B_1C_1- states with defects, that happens at the same time, in two terminals A and C or B and C; μ_1, μ_2 – repair rates.

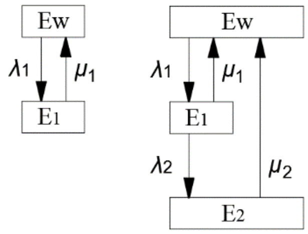




c)

Fig. 8. Graphs of states and transitions in case of fault on the protected object mode a) the system includes a DLP and DBP, b) SRP based on the CDP, c) SRP with the use of CDP and distributed protection DLP and DBP.

Convert the graphs (fig. 8) to the form shown in fig. 9. Since the damage and CT cables cannot lead to fail-to-operate protection failures, they are not included in the scheme.



a) b)

Fig. 9. Converted graphs of states and transitions in case of fault on the protected object mode a) the system includes a DLP and DBP; SRP based on the CDP, b) SRP with the use of CDP and distributed protection DLP and DBP.

The system of differential equations for the system includes a DLP and DBP and SRP based on the CDP describing the graph (fig.9, a), are similar as (1) and, accordingly, the expressions for functions of unreadiness probability and probability of failure-free operation will be similar.

The calculation for the system includes a DLP and DBP and SRP based on the CDP.

Determine the probability that the system is situated in the state E_2. The system of differential equations describing the graph:

$$\left.\begin{aligned} \frac{dP_w(t)}{dt} &= -\lambda_1 \cdot P_w(t) + \mu_1 \cdot P_1(t) + \mu_2 \cdot P_2(t) \\ \frac{dP_1(t)}{dt} &= \lambda_1 \cdot P_w(t) - (\lambda_2 + \mu_1) \cdot P_1(t) \\ \frac{dP_2(t)}{dt} &= \lambda_2 \cdot P_1(t) - \mu_2 \cdot P_2(t) \end{aligned}\right\} \quad (3)$$

Solving the system of equations (3), the unreadiness probability

$$q(t) = P_2(t) = 0{,}057 \cdot e^{-0{,}491 \cdot t} + 0{,}07 \cdot e^{-0{,}409 \cdot t} + 0{,}013$$

Graph for the calculation of assessment of the probability of failure-free operation will look similar as the graph shown in fig. 9, b, with the difference that it will not be possible transition from state E_2 в E_w.

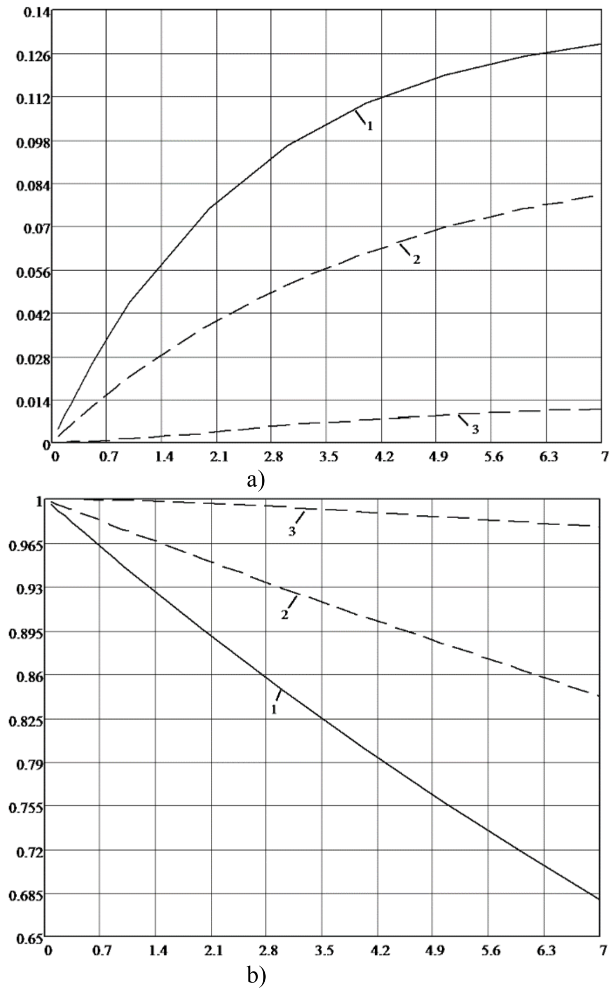
The system of differential equations describing the graph:

$$\left.\begin{aligned} \frac{dP_w(t)}{dt} &= -\lambda_1 \cdot P_w(t) + \mu_1 \cdot P_1(t) \\ \frac{dP_1(t)}{dt} &= \lambda_1 \cdot P_w(t) - (\lambda_2 + \mu_1) \cdot P_1(t) \\ \frac{dP_2(t)}{dt} &= \lambda_2 \cdot P_1(t) \end{aligned}\right\} \quad (4)$$

Solving the system of equations (4), the probability of failure-free operation

$$R(t) = 1 - P_2(t) = 1{,}009 \cdot e^{-0{,}0045 \cdot t} - 0{,}009 \cdot e^{-0{,}509 \cdot t}$$

In fig. 10 shown the dependences of the function of the unreadiness probability of SRP, and functions of the probability of failure-free operation on the average time between checks.



b)

Fig. 10. Function of the unreadiness of SRP (a) and function PFFO of SRP (b).1 - the system includes a DLP and DBP; 2 - SRP based on the CDP; 3 - SRP with the use of CDP and distributed protection DLP and DBP.

Analysis of numerical calculations of indicators of reliability of the differential relay protections (fig. 7, 10) shows:

- developed protection part of electrical network using the method of double entry, in both modes in general, has higher indicators of reliability of than technical solution with DLP and DBP;
- to increase reliability in an absence of fault on the

protected object mode in variant of the total system of with the use of CDP and distributed protection DLP and DBP, it is recommended to apply the scheme with the voting;

- the obtained calculation ratio can be used in the methods of practical reliability analysis of centralized relay protection of power substations.

4 Conclusions

Proposes a new principle of organization of the centralized differential protection of part of electrical network using the method of double entry.

This protection can adapted to changes in the configuration of the electrical network and suitable for use in the power supply circuit with sources of distributed generation.

Developed technical solutions allow to detect the current transformers and communication channels faults, and having high reliability.

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