An Approach to Assessment of the Technical Condition of Overhead Transmission Lines

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***Abstract*—The approach of estimating the current state of the overhead transmission lines is considering. The performance functions of the overhead transmission lines has been generated on the basis of experimental data and reports. Results of simulation of the approximation functions for overhead transmission lines are analyzed.**

***Keywords:* overhead transmission lines, technical condition, fractional factorial experiment.**

I. Introduction

This research package is one of the part of the decision-making informational support system of the electrotechnical equipment life cycle management based of energy-information model [1][2].

Given package is aimed at achieving the following goals:

- Assurance of tolerance of power supply systems on the basis of data-analytical decision-making environments (the task should be considered in modern monitoring providing methodology complex, diagnostics and maintenance).
- Simulation and optimization of power systems, assurance of operational reliability of power complexes.
- Organizations of operating control of electrical power networks.
- Management of life cycle of electric equipment networks on the basis of modern methods of CALS-technologies [3].

Control of efficient operation of electrical engineering systems (EESs) involves numerous factors that must be taken into consideration. The factors (parameters) to be considered must include only those that can be really controlled or varied during operation at enterprises of the branch in question [2, 4, 5].

II. Probabilistic Assessment Of Failures

Probabilistic assessment of failures is applicable predominantly to the overhead transmission lines (OLs) [2][6]. Let us consider a OL as a sequence of links, i.e., lines and towers. The operating characteristic of a link is a reduced dimensionless quantity that considers the wire strength, the time factor, operating conditions, etc.

The function of the OL distribution is characterized by the equation [2][7]

$$F(x) = P(l < x),$$

where l is the current value of the OL operating characteristic [7]:

$$l = \min\{l_1, l_2, \ldots l_z\},$$

and z is the number of the links of which the line is comprised.

The exponential law

$$F(x) = \begin{cases} 1 - e^{-\alpha z(x-l)} \\ 0,\ x \le 1 \end{cases} \tag{1}$$

is taken as the probability law where α is the generic parameter equal to the value of the response function of the line the operating characteristic of which is minimal [6][8][9].

The current value of the operating characteristic of every OL link is found by the formula

$$l_i = 1 - e^{-\gamma_i (1-T_i)^2}, \quad i = \overline{1, z}, \tag{2}$$

where γ is a generic parameter that considers different factors (the value of the response function can be used as this parameter), T_i is a parameter that considers the in-service time of the ith unit, $T_i = t_i$ is the current in-service time of the ith unit, and t_i max is the maximum in-service time of the ith unit [7].

III. Assessment Of The Technical Condition Of Overhead Transmission Lines

Assessment of the technical condition of overhead transmission lines is characterized by the following parameters [10]-[12]:

$$X_{\text{OL}} = \{x_1, \ldots, x_4\},$$

where x_1 and x_2 are the deflections of a tower from the vertical line along and across the OL, x_3 is the factor of defectiveness, and x_4 is the excess temperature.

The objects of the assessment of the OL technical condition are

$$O_{\mathrm{OL}} = \{O_1, O_2\}, \quad (3)$$

where O_1 is the maximum security and O_2 is the minimum time consumed to replace or repair the parts [7][11].

An expert arrangement of the objects' ranks for assessment of the OL technical condition is presented in Table 1 (number of the expert $N = 5$).

TABLE 1
EXPERT ARRANGEMENT OF OBJECTS' RANKS TO ASSESS OL TECHNICAL CONDITION

Expert number	Objects' ranks	
	r_1	r_2
1	1	2
2	2	1
3	1	2
4	2	1
5	1	2
R_i	R_1=7	R_2=8

Processing of rank matrix $[r_{id}]$ allows for the weight of each parameter to be assessed as

$$v_i = \frac{v'_i}{\sum_{i=1}^{N} v'_i}, \quad (4)$$

where

$$v'_i = 1 - \frac{R_i}{nN} + \frac{1}{n},$$

and n is the number of the parameters in the list [13].

The values of the weights of each object in the assessment of the OL technical condition calculated by Eq.(4) are summarized in Table 2.

TABLE 2
EXPERT EVALUATION OF WEIGHTS OF OBJECTS TO ASSESS OL TECHNICAL CONDITION

Object	Object designation	Object designation	Weight value
Maximum security	O_1	v_1	0.53
Minimum time expended for replacement and repair	O_2	v_2	0.47

Let us, applying the well-known approach to carrying out a fractional factorial experiment [7], construct for the electrical equipment of various types the response functions in the polynomial form as

$$y = \beta_0 x_0 + \sum_{i=1}^{n} \beta_i x_i,$$

where β_0, and β_i are the polynomial coefficients, x_0 is a dummy parameter (factor), $x_0 = 1$, x_i is the ith parameter in the list, and n is the number of the parameters in the list.

To assess the parameters of a OL, a fractional factorial plan of the type 2^{4-1} is used that is set by the generating relation

$$x_4 = x_1 x_2.$$

A matrix of the plant to assess the OL technical condition is constructed as

$$\overline{\mathbf{D}}^{\circ}_{4-1} = \begin{array}{c} \begin{array}{ccccc} x_0 & x_1 & x_2 & x_3 & x_1x_2 \end{array} \\ \begin{pmatrix} +1 & -1 & -1 & -1 & +1 \\ +1 & +1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 & -1 \\ +1 & +1 & +1 & -1 & +1 \\ +1 & -1 & -1 & +1 & +1 \\ +1 & +1 & -1 & +1 & -1 \\ +1 & -1 & +1 & +1 & -1 \\ +1 & +1 & +1 & +1 & +1 \end{pmatrix} \end{array}.$$

The normalized permissible values of the factors that determine the technical condition of an OL are presented in Table 3.

Determination of the factor levels ranges that determine OL technical condition is presented in Table 4.

For objects (3) effective achievement is passed:

1. The indicator for object O_1 is categorization. Factors (parameters) are assigned to the following categories (Table 5).

The values of categories of different variants in a fractional factorial experiment for object O_1 are presented in Table 6.

The effective achievement of object O_1 for each of variants is presented in Table 7.

TABLE 3
PERMISSIBLE VALUES OF FACTORS THAT DETERMINE OL TECHNICAL CONDITION

Designation	Factor	Permissible values	Optimal value
x_1	Deflection of tower from the vertical axis along the OL	1:150 - 1:75	112.5
x_2	Deflection of tower from the vertical axis across the OL	1:150 - 1:75	112.5
x_3	Factor of defectiveness	1.2-1.5	1.35
x_4	Excess temperature	5°-10°	7.5

TABLE 4
DETERMINATION OF THE FACTOR LEVELS RANGES THAT DETERMINE OL TECHNICAL CONDITION

Low level (-1)	Middle level (0)	High level range (+1)		Middle level (0)	Low level (-1)
>150	150-116.25	116.25	108.75	108.75-75	<75
>150	150-116.25	116.25	108.75	108.75-75	<75
<1.2	1.2-1.335	1.335	1.365	1.365-1,5	>1.5
<5	5-7.25	7.25	7.75	7.75-10	>10

TABLE 5
FACTOR'S INDICATORS FOR OBJECT O_1

Factor	Category
x_1	2
x_2	2
x_3	2
x_4	1

TABLE 6
THE VALUES OF CATEGORIES OF DIFFERENT VARIANTS IN A FRACTIONAL FACTORIAL EXPERIMENT FOR OBJECT O_1

Variant number	Category
1	2
2	1
3	1
4	2
5	2
6	1
7	1
8	0

TABLE 7
THE VALUES OF EFFECTIVE ACHIEVEMENT OF OBJECT O_1 FOR DIFFERENT VARIANTS IN A FRACTIONAL FACTORIAL EXPERIMENT

Variant number	Effective achievement
1	0.5
2	0
3	0
4	0.5
5	0.5
6	0
7	0
8	1

2. The indicator for object O_2 is time of troubleshooting or repair of equipment for a given parameter.

The recovery time (in days) for the elimination of invalid values for each factor is shown in Table 8.

TABLE 8
RECOVERY TIME FOR THE ELIMINATION OF INVALID VALUES FOR EACH FACTOR THAT DETERMINE OL TECHNICAL CONDITION

Factor	Recovery time
x_1	5
x_2	5
x_3	20
x_4	10

Then, assuming that the equipment at fault will be corrected at the same time, the recovery time for different variants will be as shown in Table 9 [10, 11].

TABLE 9
VALUES OF RECOVERY TIME FOR DIFFERENT VARIANTS IN A FRACTIONAL FACTORIAL EXPERIMENT

Variant number	Recovery time, days
1	20
2	20
3	20
4	20
5	5
6	10
7	10
8	0

The effective achievement of object O_2 for each of variants is presented in Table 10.

TABLE 10
THE VALUES OF EFFECTIVE ACHIEVEMENT OF OBJECT O_2 FOR DIFFERENT VARIANTS IN A FRACTIONAL FACTORIAL EXPERIMENT

Variant number	Effective achievement
1	0
2	0
3	0
4	0
5	0.25
6	0.5
7	0.5
8	1

The integrated assessment of the efficiency is calculated by the arithmetic mean form as

$$E_{a,j} = \sum_{i=1}^{s} v_i e_{ji} ,$$

where j is the variant number and s is the number of objects, estimate e_{ji} reflects the degree of achieving object O_i when implementing variant j; it is given in the range from 0 to 1 [13].

The results of calculating are presented in Table 11.

TABLE 11
SUMMARY TABLE OF EFFECTIVE ACHIEVEMENT OF OBJECTS O_1 AND O_2 IN A FRACTIONAL FACTORIAL EXPERIMENT

Variant number	**v_1 (0.53)**	**v_2 (0.47)**	**E_a**
1	0.5	0	0.265
2	0	0	0
3	0	0	0
4	0.5	0	0.265
5	0.5	0.25	0.3825
6	0	0.5	0.235
7	0	0.5	0.235
8	1	1	1

The coefficients of the response function $\{\beta i\}$ are defined by the least-squares method as

$$\hat{\beta}_0 = \frac{1}{k}\sum_{u=1}^{k} y_u \ , \ \hat{\beta}_j = \frac{1}{k}\sum_{u=1}^{k} x_{ju} y_u \ ,$$

where u is the number of the observation and

$$\{\beta_{OL}\} = \begin{pmatrix} 0.2978 \\ 0.0772 \\ 0.0772 \\ 0.1653 \\ 0.2391 \end{pmatrix}.$$

Thus, the response function for an OL has the form

$$Y_{OL}(x) = 0.2978+0.0772x_1+0.0772x_2+0.1653x_3+0.2391x_4. \quad (5)$$

Current parameters' values are stored in the database of EES' energy-information model [1].

The values of operating characteristic l for every OL assembly are found by substituting the obtained response function values into Eq.(2). The least of the obtained operating characteristic values of the assemblies is introduced into Eq.(1). Setting the required operating characteristic level, the operator calculates the probability of the failure of the OL in different time periods.

E.g., for OL "AS-95" (Voltage 35 kV, section 95 mm) with length of 11,5 km for one of EES the values of parameters (factors) that determine OL technical condition in different time periods are presented in Table 12 [10][11].

According to Table 4 these values correspond to the levels shown in Table 13.

Calculation of values of the response function $Y_{OL}(x)$ for OL "AS-95" at the time periods t_1 … t_{12} is produced by the Eq.(5) on the basis of the data in Table 12.

Further, according to the Eq.(2) operating characteristic of OL l is calculated. The results are summarized in Table 14.

TABLE 12
VALUES OF FACTORS THAT DETERMINE OL "AS-95" TECHNICAL CONDITION IN DIFFERENT TIME PERIODS

Factor	**Values of factors in different time periods**						
	t_0	t_1	t_2	$t3$	$t4$	$t5$	t_{12}
x_1	112.5	115	120	125	130	135	145
x_2	112.5	112	125	140	150	160	160
x_3	1.35	1.4	1.48	1.6	1.6	1.6	1.65
x_4	7.5	8.3	8.5	8.5	9	10	10

TABLE 13
ASSIGNMENT OF THE LEVELS TO THE FACTOR'S VALUES THAT DETERMINE OL "AS-95" TECHNICAL CONDITION

Factor	**Values of factors in different time periods**						
	t_0	t_1	t_2	t_3	t_4	t_5	t_{12}
x_1	1	1	0	0	0	0	0
x_2	1	1	0	0	0	-1	-1
x_3	1	0	0	-1	-1	-1	-1
x_4	1	0	0	0	0	0	0

TABLE 14
VALUES OF THE RESPONSE FUNCTION AND OPERATING CHARACTERISTIC OF OL "AS-95" IN DIFFERENT TIME PERIODS

Parameter	**Values of parameters in different time periods**						
	t_0	t_1	t_2	$t3$	$t4$	$t5$	t_{12}
Y_{OL}	1	0.4522	0.2978	0.1325	0.1325	0.0553	0.0553
l	1	0.335095	0.21433	0.091292	0.081304	0.030627	0.008809

We assume that all the OL's nodes are overriding and secondary, i.e., ranks for them are shown in Table 15.

TABLE 15
RANKS ARRANGEMENT FOR THE NODES OF THE OL "AS-95"

Number of node	1-10	11-20
Rank's value *r*	1	2

Then for specified operating characteristics we obtain the following values of the probability of failure of the OL (Table 16).

Dynamics of the values' changes of failure probability $F(x)$ of the OL "AS-95" for different operating characteristic's level x levels of reliability x is shown in Figure 1 (when considering the area with the number of nodes $z = 20$).

The dependences of the probability of failures when considering a lower number nodes ($z = 5$) and a large number ($z = 100$) nodes, calculated in a similar manner are shown in Figures 2 and 3.

TABLE 16
VALUES OF THE PROBABILITY OF FAILURE OF OL "AS-95" IN DIFFERENT TIME PERIODS

Operating characteristic's level, *x*	**Probability of failure of OL in different time periods**						
	t_0	t_1	t_2	t_3	t_4	t_5	t_{12}
0.1	0	0	0	0.008099	0.017308	0.065219	0.084839
0.2	0	0	0	0.096536	0.104923	0.15182	0.169622
0.3	0	0	0.070548	0.177087	0.184727	0.230397	0.24655
0.4	0	0.04951	0.146625	0.250456	0.257415	0.301695	0.316352
0.5	0	0.121036	0.216476	0.317285	0.323623	0.366388	0.379687
0.6	0	0.187179	0.280609	0.378154	0.383927	0.425088	0.437154
0.7	0	0.248345	0.339493	0.433597	0.438855	0.478349	0.489297
0.8	0	0.304908	0.393556	0.484097	0.488886	0.526676	0.53661
0.9	0	0.357214	0.443195	0.530094	0.534456	0.570526	0.57954
1	0	0.405585	0.488771	0.57199	0.575963	0.610314	0.618492

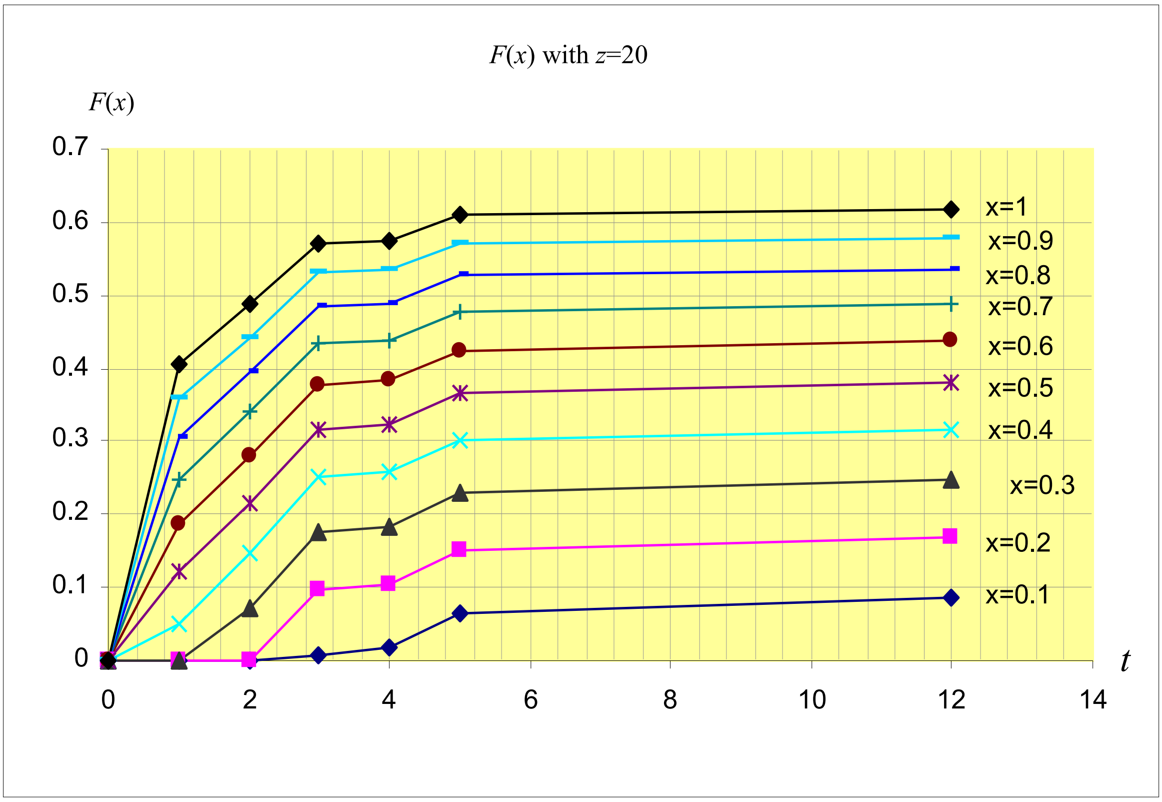

Fig. 1. Values of failure probability $F(x)$ of the OL "AS-95" when considering the area with the number of nodes $z = 20$.

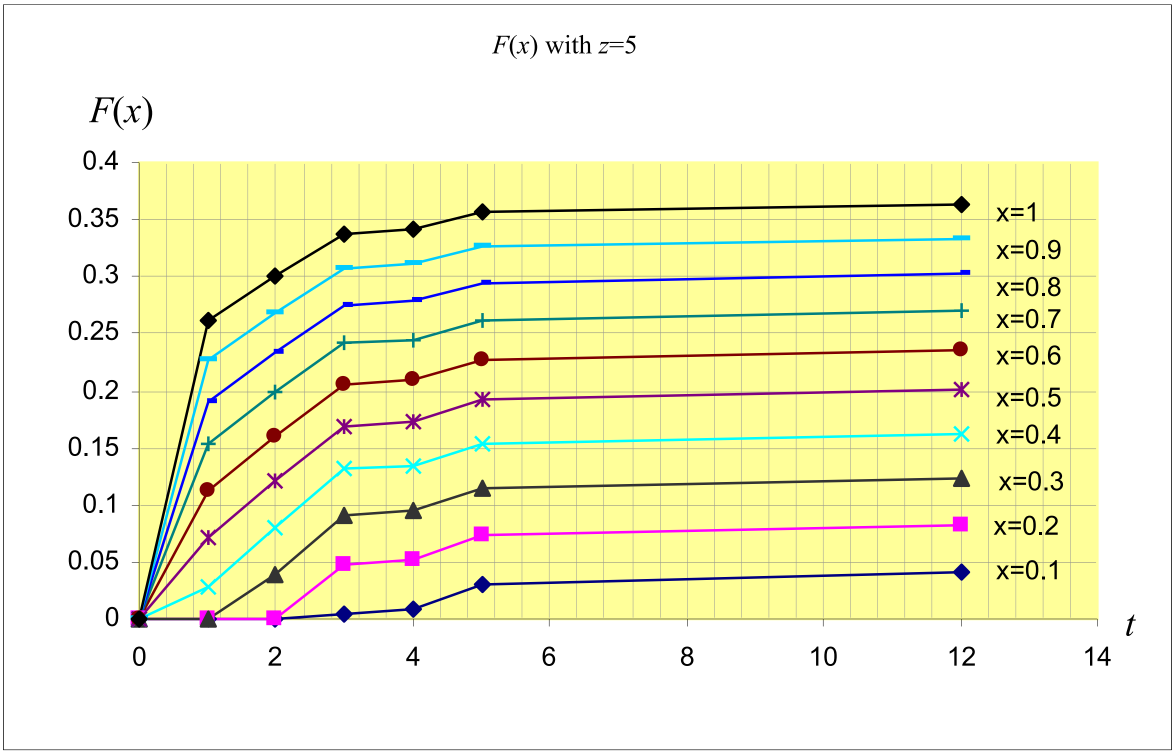

Fig. 2. Values of failure probability $F(x)$ of the OL "AS-95" when considering the area with the number of nodes $z = 5$.

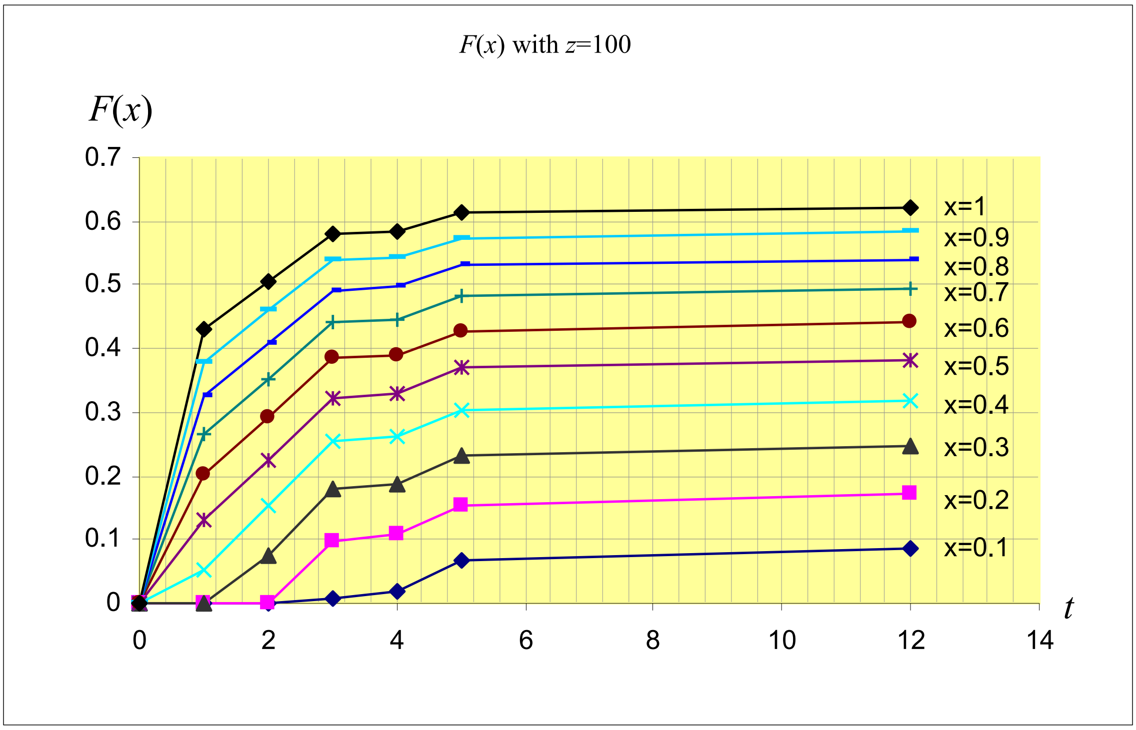

Fig. 3. Values of failure probability $F(x)$ of the OL "AS-95" when considering the area with the number of nodes $z = 100$.

IV. Analysis Of Simulation Of Approximation Functions For Overhead Transmission Lines

The problem of finding analytical dependences of the above described performance functions of the electrical equipment corresponds to the definition of the interpolation problem. On the basis of the resulting curve, the form of the approximation function is determined from a number of analytical functions with simple forms [7][14].

The mathematically best approximation entails a choice of the goodness measure, which is the residual function of nodal points and the values of the approximation function as:

$$J = \sum_{i=1}^{n} (F(x_i) - y_i)^2 \rightarrow \min$$

where y_i is the tabulated value of the assumed function at point x_i, $F(x_i)$ is the approximation function value at point x_i, and i is the number of the points, $i = \overline{1, n}$.

Analysis of the simulated approximation functions has shown that the least approximation error is obtained by the hyperbolic function $F(x) = a / x + b$ for the overhead transmission lines [7].

V. CONCLUSION

Considering the problem of usage of the information about electrotechnical equipment technical state for further repair work, it is necessary to select following levels of adequacy of estimations.

The first level – defining operating conditions according to reliability index, i.e. parameter of failure flow or reconstruction intensity.

The second level – defining technical state of the product according to probable defect characteristics and the damages revealed in a certain time.

The third level – state defining according to continuously controlled process variable, defining operating conditions of equipment elements.

According to given scheme, the basic task adds up to taking into account and dataflow management, providing data system operation [15][16].

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