Increase the Reliability of Operation of Protection DC traction substation

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Abstract. For protection of direct current (DC) traction substation is proposed to use centralized differential protection. Estimation of reliability indicators is carried out on the basis of the method of Markov chains. The obtained results allow to make a conclusion about the prospects of implementing this protection.

1 Introduction

To protect special electrical installations of DC traction substation, current protections of transformers and rectifiers [1], special DC protections [2], and ground protections are used. These technical solutions are characterized by low selectivity and outdated element base. The purpose of research is the development of highly reliable centralized differential protection (CDP) for DC traction substation.

2 Realization of proposed protection

The CDP proposed by the authors is based on the differential principle in combination with the double entry method [3, 4]. To describe the principle of protection, consider the fragment of the DC traction substation shown in fig. 1.

For the scheme (fig. 1) construct a unidirectional graph (fig. 2a) with vertices and arcs, where vertices V1 to V13 of the graph are protected items, and arcs e1 – e14, respectively, the branches of current transformers (CT), current sensors (CS) and circuit breakers. The arcs that characterize the branch of the CT, CS and switches, display the facts switching and have a weight that represents information about the magnitude flowing in the branch current obtained by measurement using the appropriate CT and CS.

The next step is the definition of range of protection based on the topology of scheme with the position of the isolators. As a result, possible transition to a new form of the graph (fig. 2b) by deleting the arcs e3-e6, e9, e10 and merge the vertices V6-8 (V6*) and V9-12 (V7*).

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.

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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 of 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, CS 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 are shown in Table 1. Variables SMV1...SMV7, obtained as a result of matrix operations, determine the conditions for the presence of short circuit in the protection zone. The SUM variable determines the total differential current.

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

| The resulting value matrix operations | Signs of fault |
|--------------------------------------|----------------|
| SUM 1 2 6* 7*                        | Fault is missing, CTS is functioning. |
| 0 0 0 0                              | Fault on V6*, V1, V2, V5. |
| 0 0 0 0                              | Fault on V7*, V3, or V4 e13 (e14). |
| 0 0 0 0                              | Fault on V1, V4 e13 (e14). |
| 0 0 0 0                              | CT Fault on e15. |
| 0 0 0 0                              | Fault on one of CS, (CT) e13 , e14, e15, e16. |

As a result, depending on the ratio of the currents in the scheme as well as results of operations on matrices it can implement the reliable operation of the differential protection of DC traction substation. This provides not only the action of protection in case of damage on each site, but excluded its excessive action when damaged current transformers and current sensors.

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 system of relay protection (SRP) [5, 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 [7]: undesired-tripping protection failures (in the absence of fault on the protected object), and fail-to-operate protection failures (in case of fault on the protected object). This approach is used in several papers, e.g. [8].

In fig. 3 presents two variants of the relay protection system organization is presented. In first case (fig. 3a) the SRP, consisting of current protections (A1, A2), earth protections (B1, D), DC current protection – (C1); in the second case (fig. 3b) - a system with application CDP (F).

![Fig. 3. Protection scheme of DC traction substation with connection of protections to CT and CS, a) standard protection scheme; b) system with the usage of CDP.](image-url)
3.1 Mode 1: absence of fault on the protected object

In fig. 4 shows graphs of states and transitions in an absence of fault on the protected object mode. Here: EW – state SRP without failures; A1, A2,…, E1 - 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,…,F, and, as a result, failure of the SRP in general; μ1 – repair rate of the protection, CS and CT.

![Graph of states and transitions for an absence of fault on the protected object mode](image_url)

Convert the graphs (fig. 4) to the form shown in fig. 5, where E1 - failure state of SRP, λ1 – the resulting failure rate of protection.

![Converted graph of states and transitions for an absence of fault on the protected object](image_url)

Table 2. Initial data for reliable indexes calculation.

| Parameter                                      | Value    |
|-----------------------------------------------|----------|
| Mean time between failures of protection      | 100000   |
| (hour)                                        |          |
| Mean restoration time of protection (hour)    | 2        |
| Queuing time (hour)                           | 2        |
| Rate of false alarms of CDP (1/year)          | 0.0307   |
| Rate of failures to trip of CDP (1/year)      | 0.0876   |
| Rate of false alarms of current protection    | 0.0307   |
| (1/year)                                      |          |
| Rate of failures to trip of current protection (1/year) | 0.0876 | |
| Rate of false alarms of earth protection (1/year) | 0.00338 | |
| Rate of failures to trip of earth protection  | 0.03     |
| (1/year)                                      |          |
| Mean time between failures of CT (hour)       | 400000   |
| Rate of CT failures including secondary circuits (1/year) | 0.0429 | |
| Rate of busbars 3,3 kV failures (1/year)      | 0.03     |
| Rate of rectifier unit failures (1/year)      | 0.25     |

A system of differential equations describing a graph, where \( P_w(t) \) - the probability of location the system in state without failures \( E_w \).

\[
\frac{dP_w(t)}{dt} = -λ_1 \cdot P_w(t) + P_f(t) \cdot μ_1
\]

(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

\[ P_w(t) + P_f(t) = 1 \]

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

\[ P_w(0) = 1, \quad P_f(0) = 0 \]

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

\[ q(t) = R(t) = \frac{λ_1}{λ_1 + μ_1} \cdot (1 - \exp[-(λ_1 + μ_1)t]) \]

(2)

Make an assessment of the probability of failure-free operation of the SRP. The graph for the calculation will look similar as the graph in fig. 5 with the difference that it will not be possible to transition from state \( E_1 \) to \( E_w \), that 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:

\[ R(t) = P_w(t) = \exp[-(λ_1 \cdot t)] \]

(3)

In fig. 6 shown the dependences of the function of the unreadiness probability of SRP, and functions of the PFFO on the average time between checks.
3.2 Mode 2: in case of fault on the protected object

The calculation of reliability indicators for the damage mode on the protected object is performed separately for the following damages using the approach described above: short circuit in the transformer, short circuit in the rectifier, short circuit on 3.3 kV buses.

Analysis of numerical calculations of indicators of reliability of the relay protection (fig. 6, 7) shows:
- developed protection in the mode 2 has higher indicators of reliability than standard technical solution on average up to 5 times;
- the obtained calculation ratio can be used in the methods of practical reliability analysis of centralized relay protection of DC traction substation.

4 Conclusions

1. Proposed a new principle of organization of the centralized differential protection of DC traction substation.
2. Developed technical solutions allow to detect the current transformers, current sensors and communication channels faults, and having high reliability.
3. Protection can be adapted to changes in the configuration of the DC traction substation.
4. The proposed technical solution can increase the reliability of the differential relay protection, what follows from by the results of practical calculations.

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