Polyhedron circuit topology switchgear as a novel complex solution

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Abstract. The paper offers and analyzes a new complex solution – open switchgear with polyhedron circuit topology, with novel circuit and arrangement approaches including new electrical equipment. Decreasing numbers of disconnectors, better structural characteristics, elimination of vulnerabilities such as sections and busbar systems are the key characteristics of this solution. Due to a new circuit topology and equipment components, the open switchgear on the whole becomes more reliable, flexible, and less costly. Examples of arrangement solutions are given. We study the data on the 220 kV switchgear component outages in one of the largest regions of Russia in the period from 2018 to 2020. The use of SF6 circuit-breakers decreases the frequency of occurrence and time of the switchgear component outages in power grids. However, it is reasonable to use transfer-busbar circuits or double-breaker circuits.

1 Introduction

Intellectualized power grids, new types of equipment, reliability, compactness, environmental friendliness, and safety should be the main features of power systems in XXI century.

The density of electrical connections has greatly grown in the developed regions, thus n-2 criterion (as extension of n-1) is being increasingly used. This criterion considers all possible combinations of outages and repairs.

In terms of n-2 criterion, switchgears will inevitably become bottlenecks of power grids. They will remain so until they contain such centralization components as busbars sections/systems with bus-coupler breakers, since centralization is not conceptually compatible with survivability. Thus, power grid architecture should be developed.

There are high requirements to switchgears in terms of their design, functionality, user-friendliness. They are the framework of a power grid as their parameters are of strategic value.

Schemes, design and arrangements of switchgears were described in the 1960s-1980s [1,2], were studied in the 1990s-2000s [3-5]. The reported works are still relevant today. Switchgear circuits which are currently used in substations are found in [6]. The object of this study is 110-220 kV open switchgears.

According to [7], the way the power grids of the future will look like will depend on the conditions of their development and functioning. Scales of power grids grow, service areas increase, different power systems merge. Simultaneously, electricity consumption is distributed throughout the country. Decentralization trend is observed in terms of generation. Thus, current principles of development and construction of power grids will require new approaches.

The report offers ways to increase reliability of open-type switchgears due to a novel topology. The following issues were considered:

- a new solution and its key characteristics were described;
- possible realizations were studied;
- factual data on outages were analyzed, the effects of introduction of SF6 circuit-breakers (CBs) on repair characteristics of switchgears were assessed;
- a combination of outages of open switchgears and switching applications was modelled.

2 Methods and materials

Analogy, elements of systems theory, graph theory and reliability theory were used in the study. Power industry of the future will require novel approaches, thus there appeared an attractive hypothesis to use a topology of one of the most known biological structures – DNA molecule (Fig.1).

As can be seen, a DNA structure is topologically equivalent to that of a polyhedron, namely of polygonal prism. Polyhedron structure is highly cohesive, however decentralized. This structure can be realized as switchgear of a new type in the following way: each switching application is done through a junction of disconnectors, thus the switching application and its disconnectors form an edge. Circuit breakers are put in the vertices of a polyhedron. Each vertex connects no more than three edges. The switching application is broken with breakers of incident vertices.

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The switching application in the new-type switchgear is repaired by switching off two disconnectors. Breakers are repaired by switching off three disconnectors which are adjacent to the vertex, i.e. the polyhedron vertex as a whole is put under repair without an outage of the switching application.

According to the connection conditions in the three-edge vertex, at least two circuit breakers (CBs) or a special device – 3D-circuit-breaker (3D-CB) are put in each vertex.

3D-CB is a circuit breaker which has three primary terminals for different circuits. The main contacts of breaking units are connected following the star-scheme, whose arms have primary terminals thus making 3D-circuit breaker. This circuit breaker can use elements of current commercial CBs. In addition, a support structure, a foundation and an operating mechanism are not necessary (Fig.2). This will help new equipment to avoid many problems. The cost of the live-tank type 3D-CB is predicted to be 150-190% of the conventional commercial live-tank type CB cost.

Currently, the most unreliable and problematic element of the switchgear is disconnectors since further improving their reliability is limited [8]. Decreasing number of critical components is already a noticeable advantage.

Thus, new circuit topology and equipment components are the key characteristics of the novel solution, which is expected to improve reliability, flexibility and cost-effectiveness. This will be done not only by decreasing a number of disconnectors, but also by eliminating such vulnerabilities as sections and busbar systems, as well as by improving structural characteristics of the switchgear. This will be illustrated below.

Structural characteristics are a part of topological methods of reliability assessment and are not used in the design practice as such, since they do not allow further technical-and-economic assessment of options. These parameters are of value due to the fact that they have been obtained only on the base of the data on the element composition and their connections. Ref. [9] names the following structures applicable in power industry: series, ring, radial, complete graph, disconnected circuits. Characteristics of a cube as an example of polyhedron were calculated in comparison with the reported circuits (Table 1).

Table 1. Structural topological characteristics of different circuits.

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Parameter</th>
<th>$R$</th>
<th>$K_C$</th>
<th>$\varepsilon^2$</th>
<th>$Q$</th>
<th>$d$</th>
<th>$\delta$</th>
<th>$\gamma_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>series</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1,2</td>
<td>1</td>
<td>4</td>
<td>0,67</td>
<td>0,25</td>
</tr>
<tr>
<td>ring</td>
<td></td>
<td>0,25</td>
<td>2</td>
<td>0</td>
<td>0,5</td>
<td>2</td>
<td>0</td>
<td>0,2</td>
</tr>
<tr>
<td>radial</td>
<td></td>
<td>0,1</td>
<td>1</td>
<td>7,2</td>
<td>0,6</td>
<td>2</td>
<td>1</td>
<td>0,5</td>
</tr>
<tr>
<td>tree-like</td>
<td></td>
<td>0</td>
<td>1</td>
<td>3,2</td>
<td>0,75</td>
<td>3</td>
<td>0,76</td>
<td>0,38</td>
</tr>
<tr>
<td>complete graph</td>
<td></td>
<td>1,5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0,25</td>
</tr>
<tr>
<td>disconnected</td>
<td></td>
<td>-</td>
<td>0,25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,25</td>
</tr>
<tr>
<td>polyhedron</td>
<td></td>
<td>0,71</td>
<td>2</td>
<td>0</td>
<td>0,71</td>
<td>3</td>
<td>0</td>
<td>0,13</td>
</tr>
</tbody>
</table>

First three parameters are important for power industry objects. Parameter $R$ (structure redundancy) is an indirect assessment of reliability and cost-effectiveness, it makes the system function and preserve its connections when some of its elements malfunction. The system with a higher redundancy is supposed to be more reliable. Parameter $K_C$ (connectivity) is a characteristic of possible fault and repair of an element. Parameter $\varepsilon^2$ (quadratic deviation of vertex degree distribution) characterizes underutilization of the structure capacity and indirectly assesses cost-effectiveness.

The obtained parameters show that the polyhedron circuit is more cohesive, reliable, flexible, cost-effective, open and scalable. The polyhedron structure is very similar to the reference structure of complete graph in terms of parameters. Hence, the new-type switchgear parameters will not limit, but in contrast enhance intellectualization of electrical grids.
3 Implementation

Configurating a switchgear is arranging electrical equipment in a specific order in accordance with its functions and current requirements, and interconnecting its parts following the scheme. A switchgear typically consists of a number of analogous switching applications. Thus, it is sufficient to consider only one typical cubicle and the way these are connected with each other.

Convex polyhedron can always be shown as a flat graph with any number of switching applications and without intersecting edges.

A cube is a good example of the proposed structure. A simplified scheme of such switchgear is given in Figure 3. Eight vertices are required for twelve switching applications. In conventional circuits, a total number of CBs is 13-14.

Arranging the vertices in two rows along the passage for their maintenance is convenient and descriptive for an open switchgear with polyhedron topology (Fig.3).

![Fig. 3. An example of an open switchgear circuit with a cube topology](image)

The switchgear of a new type has a modular structure. For 110kV, it is viable to make a polyhedron vertex as a module of block structure (Fig. 4). Fig. 5 shows an open-type 110 kV switchgear arrangement.

![Fig. 4. An example of a module of block structure of a new-type open switchgear](image)

Fig. 5. Arrangement of a novel open 110 kV switchgear

An example of a 220 kV switchyard is shown in Fig.6. Primary terminals in the middle of a 3D-CB are connected via elements of a rigid busbar.

![Fig. 6. 220 kV switchyard with a 3D-CB](image)

Fig. 4-6 show that arrangement of the novel open switchgear is in agreement with the conventional rules, which meets all necessary conditions. In terms of compactness, it is better or at least not worse than its analogs. A polyhedron structure is not bulky.

Thus, an idea of a fewer number of connectors, absence of vulnerabilities, better structural characteristics of the novel open-type switchgear appears to be valid.

4 Discussion

For recent 30 years numerous SF6 CBs have been installed in the Russian power grid. At the early stage of their use, they were expected to decrease the frequency of occurrence and time of switchgear outages in such a way that they would be assimilated by switching application outages. Today we can see whether these expectations have come true.

Little attention is typically paid to outages, their data are often inconsistent and contradictory. For instance, the data from [10] and [11] have been used since the 1980s. Both sources refer to recommendations of ORGRES firm, the data however are inconsistent.

The author of this paper considered cases of repair of switchgear elements in one of the largest regions of Russia (over 150 substations, over 1,000 CBs in different climate zones) in 2018-20 – in total 3,777 outages in 220 kV open-type switchgears. Only minor maintenance and medium maintenance repairs in the switchgears where CBs were not changed in the reported period were analyzed. Major repairs were not considered since such repairs for ageing types of CBs
are not made at present, and change of CBs is a part of such repairs. The obtained indicators are presented in Table 2.

The current indicators are in correspondence with those from [10], whereas they differ by 9-12 times from the ones in [11].

Advantages of SF6 CBs are remarkable. However, great changes by an order or higher has not been found. For instance, a mean time of an outage of a cubicle of an open 220 kV switchgear with a live-tank SF6 CB is 105 hours, that of the one with an oil CB is 137 hours. The obtained data are generally in agreement with those from [5, pp.43-45].

Table 2. Repair parameters of elements in an open 220 kV switchgear.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>2</td>
<td>2</td>
<td>0.2 0.14 0.14 1.77 1.73 1.61 1.18 1.13</td>
</tr>
<tr>
<td>Oil</td>
<td>88</td>
<td>37</td>
<td>96</td>
</tr>
<tr>
<td>Dead-tank oil</td>
<td>142</td>
<td>137</td>
<td>148 97 105</td>
</tr>
<tr>
<td>Delay-tank SF6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live-tank SF6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outage data according to electrical equipment types are given as a fractional number in Table 3. The numerator of the fraction is a percentage of the total number of the operations done in all outages, the sum in it is 100 %. The denominator of the fraction is a percentage of the total number of outages, the sum in it is higher than 100 %. For example, CTs have 17 % of the total number of cases, whereas CTs are involved in 25 % of outages. In approximately 45 % of outages, the work was done simultaneously in several electrical devices.

Table 3. Outage data of open 220 kV switchgear elements.

<table>
<thead>
<tr>
<th>CB</th>
<th>CT</th>
<th>BD</th>
<th>LD (TD)</th>
<th>BD</th>
<th>SC</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>37%</td>
<td>17%</td>
<td>19%</td>
<td>11%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>100%</td>
</tr>
<tr>
<td>53%</td>
<td>25%</td>
<td>28%</td>
<td>16%</td>
<td>12%</td>
<td>9%</td>
<td>145%</td>
<td></td>
</tr>
</tbody>
</table>


Fig.7 shows distribution of repair time of open 220 kV switchgear elements. This graph is of interest because it is identical to a similar graph for overhead power transmission overhead lines from [13], both have exponential distribution which is found when a distribution of accident events occurs. This means that two independent, accidental in time occurrences should be brought into coincidence.

Independence of the occurrences of outages makes their synchronization very difficult. Based on this, synchronization was modelled (the occurrences were mixed and compared), the time of the total outage was taken as the maximum one from the two ones (the receiving end of a power transmission line was not considered by convention). For power transmission lines the repair time distribution was taken from [12], for open switchgear cubicles the data were collected in this work (for SF6 CBs).

The time of the synchronized outages was longer on average by 60 %. The results of modelling are in correspondence with the factual data in which switchgear outages and connection outages are brought into coincidence.

Thus, the use of SF6 CBs decreased the frequency of occurrence and time of outages of open switchgear elements in power grids on the whole. However, it is still not viable to synchronize outages, instead it is reasonable to use circuits with transfer busbar systems or schemes with two CBs on a switching application, an example of which is a polyhedron circuit.

5 Conclusion

A new complex solution – a switchgear with polyhedron circuit topology – includes novel scheme and arrangement approaches as well as new equipment – 3D-CBs. These breakers can be produced at one of the Russian factories. New-type switchgears are expected to be more reliable, flexible, cost-effective and compact.

For 3D-CBs to be used in new open switchgears, they should be designed, manufactured and factory-tested.

It is viable to study this new-type open switchgear and to do a pilot project in order to make a decision on further commercialization of this technical solution.

New-type switchgears can be used in constructing new and re-constructing current switchgears which have 5 or more switching applications. Due to cohesive structure of a polyhedron, it is reasonable to use it in circuits with parallel operation: in 110 kV grids and higher-voltage grids, as well as in generation switchgears. In separate operation grids (6-35 kV switchgears) such switchgears can become an alternative to busbar sections.

Arrangement of novel open switchgears is in agreement with the conventional rules, which meets all necessary conditions. In terms of compactness, they are better or at least not worse than their analogs.

We considered current indicators of outages of
open-type 220 kV switchgear elements in one of the largest regions of Russia in the period from 2018 to 2020. Even taking into account the use of SF6 CBs, which decreased the frequency of occurrence and time of outages of open-type switchgear elements, it is still viable to employ circuits without synchronizing switchgear outages and those of switching applications.

The offers presented in the report open new opportunities to study the important issue which can generally improve reliability of power grids.

References

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