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# THE METHOD FOR DETERMINING THE EFFECTIVE TOTAL LOAD SHEDDING FOR UNDER-FREQUENCY LOAD SHEDDING OF THE POWER SYSTEM

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***Abstract.*** *This paper suggests a method for determining the effective total amount of load disconnection in case of major frequency drop and under-frequency load shedding (UFLS) activation.*
*A mathematical model of power balance in emergency areas has been developed, which uses the structure of the electric network scheme.*
*The UFLS is presented in the model by a set of frequency relays with fixed consumer loads behind feeders along the year and binary variables triggering their operation.*
*The solution of the integer linear programming problem provides the optimal set of the relays needed to balance all emergency areas given the minimum total load shedding (TLS).*
*This determines both the TLS and the placement of individual relays in the electrical network.*
*The method involves pre-measurement of the consumer loads behind feeders, as well as power flows in the network for its characteristic modes.*
*For this purpose, standard specialized software is used to calculate stationary modes and contingency analysis.*
*The input data for the simulation is also a set of electrically unconnected emergency areas.*
*This information should be provided by the user of the proposed method by indicating the overhead line cross-sections in electric network.*
*The developed method allows to determine the TLS of UFLS and the most efficient set of frequency relays for any power system in order to align these indicators with the requirements of the National Electricity Transmission System Operator.*

***Keywords:*** *Under Frequency Load Shedding (UFLS), Low Frequency Demand Disconnection (LFDD), Total Load Shed, Total Percentage Demand LFDD.*

# МЕТОД ВИЗНАЧЕННЯ ЕФЕКТИВНОГО ОБСЯГУ АВТОМАТИЧНОГО ЧАСТОТНОГО РОЗВАНТАЖЕННЯ ЕНЕРГОСИСТЕМИ

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***Анотація.*** *Система автоматичного частотного розвантаження (АЧР) є єдиним засобом, який широко застосовується в енергосистемах для стримування швидкого падіння частоти. Система АЧР здатна майже раптово відключити частину споживачів та зупинити падіння частоти в районах енергосистеми, які утворилися в результаті каскадного відключення ліній і генераторів. Для підтримки тимчасового балансу активної потужності в аварійних ситуаціях в енергосистемі повинна бути передбачена кількість навантаження на відключення.*

*Тому оператори систем передачі або мережа операторів систем передачі електроенергії встановлюють так званий загальний обсяг розвантаження (ЗОР). Найчастіше в стандартах та нормативних документах енергосистем цей показник розраховується в умовах загального пікового попиту. Водночас ЗОР рекомендують розмістити в енергосистемі рівномірно, з урахуванням географії мережі. Такий спосіб розміщення загального обсягу розвантаження не враховує електричної структури електромережі, добової та сезонної зміни генерувальних потужностей і споживання, не зважаючи на те, що стандарти та нормативні документи вимагають це враховувати.*
*В роботі запропоновано математичну модель і спосіб визначення ЗОР системи АЧР та його розміщення в мережі енергосистеми з урахуванням розподіленої генерації, ймовірних варіантів аварійного поділу енергосистеми, контрольованих перетинів вимог міжнародних стандартів та нормативних документів, що регулюють функціонування систем протиаварійного захисту в галузі електроенергетики. Модель являє собою задачу цілочисельного (бінарного) лінійного програмування, що здійснює вибір оптимального набору пристроїв АЧР, які розміщені у наперед заданих вузлах енергосистеми й спрацювання яких забезпечує баланс потужності в аварійних районах її поділу. Електричні параметри усталених режимів, а також ефективність оптимального обсягу та розподілу розвантаження в мережі визначаються й перевіряються (верифікуються) у серії апріорних та апостеріорних розрахунків на точних математичних моделях, визнаних у світовій практиці програмних продуктів електроенергетики.*
*Отриманий таким чином розподіл обсягів розвантаження підвищує ймовірність балансування якнайбільшої кількості аварійних районів енергосистеми за умови задоволення вимог щодо частотно-часової зони відповідних перехідних процесів.*

***Ключові слова:*** *енергосистема, автоматичне частотне розвантаження, знеструмлення, блекаут.*

**I. Introduction**

Over the last decades, all large-scale accidents in national TSOs with a large frequency drop, were cascading failures [1-3].

The emergency was initiated by cascading lines tripping. As a result, the system split into electrically unconnected areas not balanced by the emergency automation system. And for that reason, the operation of part of the TSOs ceased. [3, 4].

At the same time, there has been no frequency collapse in the entire power system (without cascade shutdown in the power system) in recent decades.

This can be explained by the fact that modern power systems have such a large total capacity of generating units that the failure of a single one or even an aggregation can reduce the frequency but will not cause a fast frequency drop.

For example, let us consider the 2019 emergency in the UK [10] or the 2021 emergency in the European Network of Transmission System Operators (ENTSO-E) [11].

In the first case, the UK power system was not divided into parts. None of the transmission lines were overloaded.

The rate of frequency reduction was slow, but at the time of the accident there was not enough backup generation to balance the power system [15].

Therefore, the frequency reduction was suspended by the first stage Low Frequency Demand Disconnection (LFDD) with 48.8Hz relay settings (in the report “LFDD” [10] corresponds to “UFLS” [5, 6, 11], and “stage” 10] to “step” [5, 6, 11]).

The first stage of UFLS had 5% of total demand in England & Wales.

The other emergency divided the power system into two parts.

After the separation of North-West and South-East electric power flows by ENTSO-E, the frequency in the North-West area fell to merely 49.74 Hz.

At the same time, the frequency in the South-East area initially increased up to 50.6 Hz [11].

It can be argued that frequency drop to the set point of UFLS is unlikely, if the power system is not divided by the emergency. A modern power system remains stable until its cascading division begins.

On the contrary, isolated areas of cascade shutdowns, electrically separated from the main body of the power system, may experience quite large imbalances of active power.

A large imbalance may cause a blackout if the emergency automation is not able to balance the mode in some isolated part of the power system and thus complicates the process of power system restoration.

To reduce the time to restore the power system after a disturbance with large-scale consequences, it is necessary to balance the separated areas.

Analysis of large-scale emergencies observed during blackouts worldwide [1] allows us to see the following characteristic sequence of changes in the power system when the frequency plummets or soars:

1. Emergency shutdown of a power plant or power plant unit or power line;

2. Redistribution of active power deficit between the remaining generators;
3. Change of power flow distribution in power lines;
4. Disconnection of the power line due to overload or instability;
5. Sequential cascading disconnection of power lines;
6. Division of the power system into unbalanced areas: some with excess generation capacity and some with power deficit.

For their part, emergencies in already island areas have their own special features depending on their excess or deficit of capacity.

**I. Development of an emergency in an area with excess generating capacity:**

Scenario 1

1. The frequency has increased by no more than 1.0 Hz;
2. The node voltages are within acceptable values;
3. The automation efficiently regulates frequency and voltage, the area is well-balanced;

Scenario 2

1. The frequency or the voltage increased up to the level of automatic tripping of generating units;
2. Automatic tripping of generating units;
3. An area with an excess of generating capacity becomes an area with a deficit of generating capacity;
4. The emergency develops as in an area with a deficit of generating capacity.

**II. Development of an emergency in an area with a deficit of generating capacity:**

Scenario 1

1. The frequency plummets;
2. The effective operation of UFLS restores power balance.

Scenario 2

1. The frequency plummets;
2. The UFLS disconnects much more power than necessary for balancing the scheme;
3. An area with a deficit of generating capacity becomes an area with an excess;
4. The emergency develops as in an area with an excess of generating capacity.

Scenario 3

1. The frequency plummets;
2. The UFLS cannot stop the frequency drop;
3. A blackout occurs.

It can be seen from the outage scenarios for the course of accidents, there is a probability that redundant areas at the beginning of the emergency transition process may become deficient during its further development, and conversely, previously deficient areas may become redundant. Besides that, the system may have successive processes of subsequent division of selected areas into smaller parts.

Thus, to provide for balancing as many as possible areas within a system undergoing failure with fluctuating frequency it is necessary to consider the whole volume of the operating reserves in every isolated area regardless of the deficit or excess of capacity at the beginning of the transitory period.

An operating reserve of a power system has a fairly wide time range. However, within the task of distributing the reserved volume of the automatic frequency demand one can easily regard only the capacity of the segment operating jointly with the UFLS system. Thus, Table 1 presents only the operating reserve of the power system which can be engaged within the acceptable emergency frequency-time range, from 0 to 60-100 s.

In order to investigate any accident with frequency fluctuations, the transitory process is divided into two time intervals. In the first one (zero to roughly 5-10 s), the possibility to contain the frequency decrease is studied, while in the second one (10 to 60/100 s) the possibility of stabilizing it at a level close to the nominal value is researched.

The first factor slowing down the rate of frequency decrease is the consumers who provide the regulatory effect of demand (Table 1). The effect depends on the proportion of engines in the load and the types of mechanisms being so operated. A 1% decrease in frequency is known to decrease the load by 1 to 3%. Thus, when frequency reaches the UFLS relay without time delay, the power of the load can drop by 2-6%. The extent of this reserve can not be foreseen yet it has a perceptible effect if the relative deficit of active power is not large. It upholds the frequency at a level above the high UFLS relay without time delay, blocking the consumers from being disconnected until the generation reserve capacity is put into operation (Table 1).

**Table 1. The operational reserve of power system**

| Number and name of frequency reserve | Time required to start of operation |
|---|---|
| 1. The potential of electrochemical batteries for bulk energy storage | in under 1 second |
| 2. Spinning reserve in the form of rotating machines (part-loaded, synchronised plant) | 5 – 15 seconds |
| 3. Shunting power | 20 – 30 seconds |
| 4. Load reduction due to under Voltage & Frequency (influence on dynamic properties of the load) | immediate reserve |
| 5. Rate of Change of Frequency (RoCoF) | in under 1 second |
| 6. The consumers connected to the UFLS without time delay | in under 1 second |
| 7. The consumers connected to the UFLS with time delay | more than 5 seconds |

The next reserve to be activated is the additional df/dt function in UFLS relays [5]. As a rule, this reserve (additional df/dt function in UFLS relays) is combined with part of the reserve of the UFLS relay without time delay. As an exception, this automation can also have its own individual reserve. When these two reserves are triggered and depending on the exact settings of relays in the area, the transient process follows one of two scenarios. In one case, the local reserve will slow down the frequency drop in the area, after that it recovers to its nominal value. In the other case, the frequency drop is slowed down but its recovery is either distributed over the reserve generating capacity and the UFLS relays with disconnection delay or, alternatively, provided by only one of these reserves alone.

The efficiency of use of these reserves determines whether the frequency can be maintained within the acceptable time-frequency area until the reserve generating capacity and UFLS relays with disconnection delay are engaged.

The generation capacity reserves and UFLS relays with disconnection delay should ensure that the frequency is increased without breaking the limits of the time-frequency area. To this end, it is necessary to have such reserve capacity in every given area. The lack of exactly this kind of reserve capacity can lead to secondary frequency drop and subsequent blackout.

Most power systems in the world do not employ UFLS relays with disconnection delay, including the systems of ENTSO-E member countries [5, 6]. In these power systems, the preference is given to consumers, that is, the number of disconnections is minimized through installation of sufficient reserve of generating capacity. According to the authors, this reduces the power system's reliability as the adequacy of generating capacity reserve for the power system as a whole does not always guarantee its adequacy in every single area and for any single power supply mode.

Currently, UFLS relays with disconnection delay are used only where resource constrains do not allow for some operational reserve of generating capacity to balance the power system.

With this in mind, we conclude that among all kinds of capacity reserves presented in Table 1, only the operational reserve of consumers connected to the UFLS relay without time delay can halt a rapid frequency drop given substantial deficit of active power.

Therefore, the UFLS relay without time delay is the only anti-emergency automation tool in the power system capable of containing the frequency plummeting. Within a few seconds, UFLS relay without time delay can disconnect a sufficient portion of consumers and balance the deficient areas of the power system formed as a result of a cascading failure involving the disconnection of lines and generators.

**II. Problem statement**

The UFLS disconnects groups of consumers sequentially and according to the assigned categorical value. To successfully prevent a deep frequency drop, the system should be outfitted with the required amount of load-shedding capacity to guarantee a temporary active power balance in every isolated area of the power system.

With this aim in view, the national transmission system operators (TSOs) or the network of transmission system operators (NTSO) set the value known as the total load shed (TLS) [7] or total load quantity (TLQ) [6]. In various power systems worldwide, between 30% and 60% of the total consumer capacity is connected to the UFLS system [5, 7, 10, 12]. This value is entered into the power system's standards in a general and prescriptive manner through policy regulations. As a result, it is not always clear from which consumer capacity the specified percentage is calculated. Most often, TLS is calculated as a percentage of the maximum system load. This approach, for instance, is used in the power systems of the Great Britain and Ukraine [10, 14].

TLS thus defined is commonly advised to be distributed over the system uniformly and according to the so-called “geographic principle” [5,6,10]. However, despite the possibility to “geographically distribute” frequency relays over a country's territory or a power system, it is in any case essential to integrate the UFLS-connected consumers' capacities based on their weights in some basic electricity transmission modes with appropriate justification for selecting the same modes specifically for evaluating the load shed limits.

It is clear that the above-mentioned ways to determine TLS and its distribution in the power system do not take in consideration the specific features of the structure of its electrical connection scheme or daily and seasonal variations in generating and consuming capacities despite the fact that power system standards require these factors to be addressed [5, 6, 8]. Another overlooked parameter is the probability of the design fracturing into unbalanced emergency areas.

Thus, when constructing the UFLS system, the load shed is shared over as many consumers as possible. Clearly, the capacity connected to every single relay varies throughout the year. Therefore, while the total load shed depends on the current power system operating mode, at any given moment its value in relative units cannot be lesser than the value stated in the requirements of the system operator or the joint power system [5, 8]. Hence, the above-mentioned TLS value in % can be regarded only as a generalized potentially attainable limit for the UFLS system of the entire power system. The value does not provide informative insight into the efficiency of the involved consumer load capacity. Using TLS as an indicator of the sufficiency of load shedding in the general case does not guarantee preventing a failure since in the event of the power system scheme split and the activation of frequency load shedding in the emergency mode, some areas may turn out to be insufficiently outfitted with the required amount of load shed due to the specifics of the power system scheme and the boundaries of electrically isolated emergency areas.

To provide a sufficient load shedding in every emergency area at any TLS activation time, it is needed to determine its value taking into account the structure and amounts of generating and consuming capacities, schemes of the electrical connections, variable capacity of consumers connected to frequency relays, basic modes' parameters (including those occurring at the maximum and minimum power system load).

In this study, the criterion of TLS distribution efficiency is the minimum load shed required in the power system, considering the probability of its split into, generally speaking, arbitrary isolated emergency areas.

To solve the problem of TLS minimization, it is necessary to use a model of the power system to calculate its common regimes. A mathematical model allows to compute the net power flow through power lines at the split points of the emergency areas and the deficit of active power in them. To incorporate load shed changes created by TLS it is proposed to analyze three basic power system modes: the maximum and minimum loads and also the mode in which the share of distributed generating capacity from renewable energy sources is maximized in the structure of the total generating capacity.

Using the scheme of power system's connections, the boundaries of the affected areas are shown, and, using the informational model of the UFLS system, the sets of load shedding devices are determined together with the respective amount of capacity of connected consumers in these areas. The UFLS dataset is shown in Table 2 based on measurements taken in the distribution network for the three basic modes chosen.

**Table 2. Fragment of the list UFLS relays with settings and amount of load shedding in three basic modes**

| | **Nodes of network** | **The frequency and time of the relay setpoints** | | **Mode of Power System** | | |
|---|---|---|---|---|---|---|
| **Substation** | **Feeders** | **Hz** | ***S*** | **1*** | **2**** | **3***** |
| | | | | **MW** | | |
| DTS 110/35 -1 | 169 | 49,0 | *0,15* | 2,4 | 2,5 | 3,2 |
| | 169-01 | 49,0 | *0,15* | 0,1 | 0,3 | 0,1 |
| | 169-05 | 49,0 | *0,15* | 0,3 | 0,5 | 0,6 |
| | 169-14 | 49,0 | *0,15* | 0,1 | 0,2 | 0,2 |
| | 169-10 | 49,0 | *0,15* | 0,3 | 0,3 | 0,5 |
| | 169-11 | 49,0 | *0,15* | 0,3 | 0,5 | 0,8 |
| | 169-17 | 49,0 | *0,15* | 0,2 | 0,6 | 0,7 |
| | 169-19 | 49,0 | *0,15* | 0,1 | 0,1 | 0,3 |
| DTS 330/35- 5 | **166** | 48,2 | *0,15* | 0,3 | 0,7 | 0,9 |
| | 166-06 | 48,2 | *0,15* | 0,2 | 0,6 | 0,8 |
| | 166-08 | 48,2 | *0,15* | 0,1 | 0,1 | 0,1 |
| DTS 330/35-2 | **165** | 48,7 | *0,15* | 1,1 | 0,7 | 2,5 |
| | 165-05 | 48,7 | *0,15* | 0,3 | 0,4 | 0,7 |
| | 165-06 | 48,7 | *0,15* | 0,5 | 0 | 0,8 |
| | 165-07 | 48,7 | *0,15* | 0,3 | 0,3 | 0,6 |

**1 – the mode of the total peak demand of the power system;*
***2 – the mode of the total low demand of the power system;*
****3 – the mode with the total peak capacity of distributed generation.*

Thus, the task of determining TLS and its placement in the distribution power system has its own specifics for every power system under study. To find an efficient solution, a certain sequence of steps must be followed including calculation, preparation and organization of the data support, modeling the capacity balance in the power system divided into arbitrary emergency sections, and a final computational verification of the efficiency of load shedding given the capacities determined earlier during the balancing of capacities and UFLS devices' arrangement phase.

For ease of use, the sequence is presented as a coherent algorithm of TLS determination shown as a flowchart in Fig. 1.

Block 1 describes the operation of measuring consumer capacities for the three basic power system modes - the maximum and minimum load and the mode with the maximum share of distributed generation. The measurement results obtained in the distribution network at this stage are recorded in Table 2 which has the following structure. The Mode column includes:

1. capacity of the substations and connections when the power system operates in the minimum load mode:
2. capacity of the substations and connections when the portion of distributed generation of renewable energy sources is maximum in the generating structure;
3. capacity of the substations and connections when the power system operates in the maximum load mode.

The Relay column contains the de facto frequencies and times of engagement of the acting settings of the UFLS.

Block 2 shows the preparatory stage of the set of possible scenarios for dividing the power system into emergency areas, which are subject to analysis to define and adjust the TLS distribution. To this list, we add the scenarios of power system division, each presented as a list (set) of lines of the protection scheme that could sequentially disconnect in the event of a cascading failure. Primarily, such lines could include the controlled crossings (see Fig. 2, secants IV-IV and V-V). Besides that, considering the fact that it is practically impossible to predict exactly which lines and in what sequence are going to be disconnected as the failure develops [9], it is advisable to consider scenarios involving somewhat arbitrary divisions shown in Fig. 2 by secants 1-1, 2-2, 3-3 and 4-4.

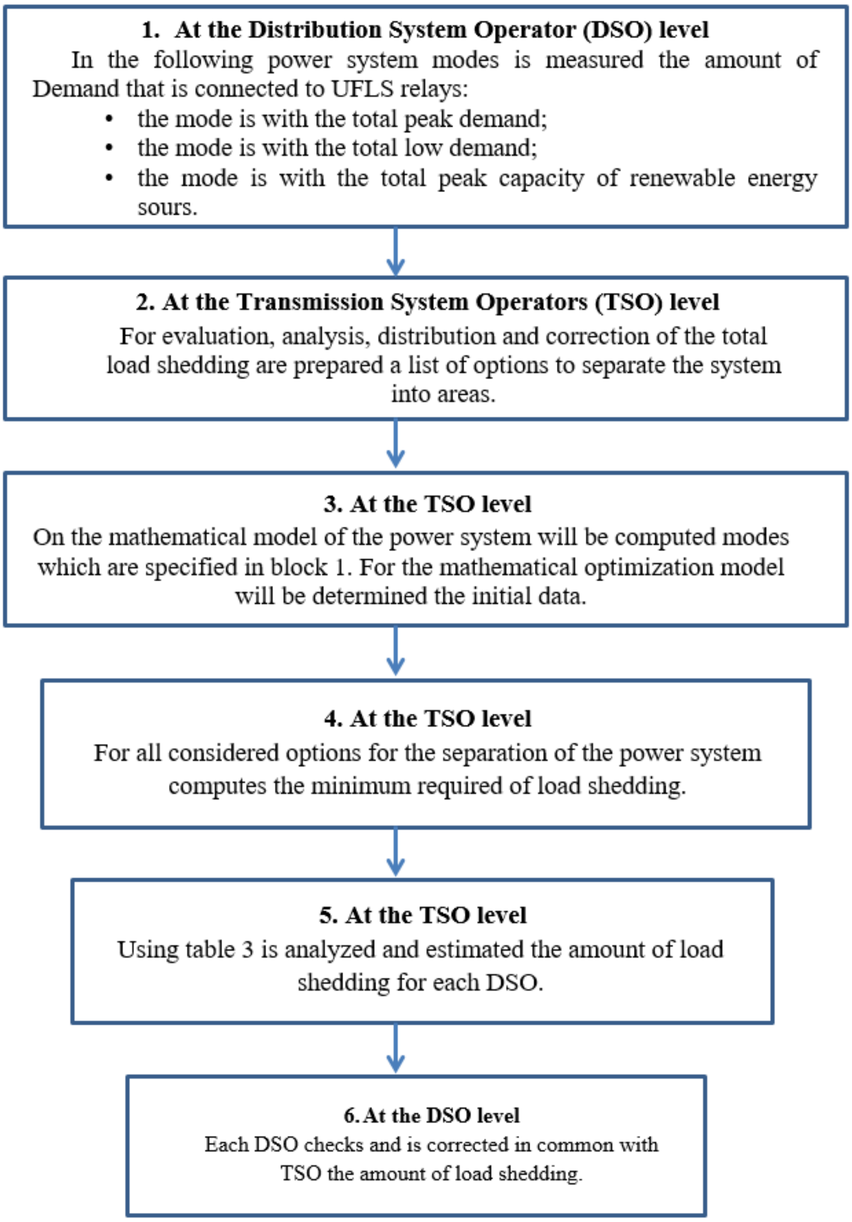
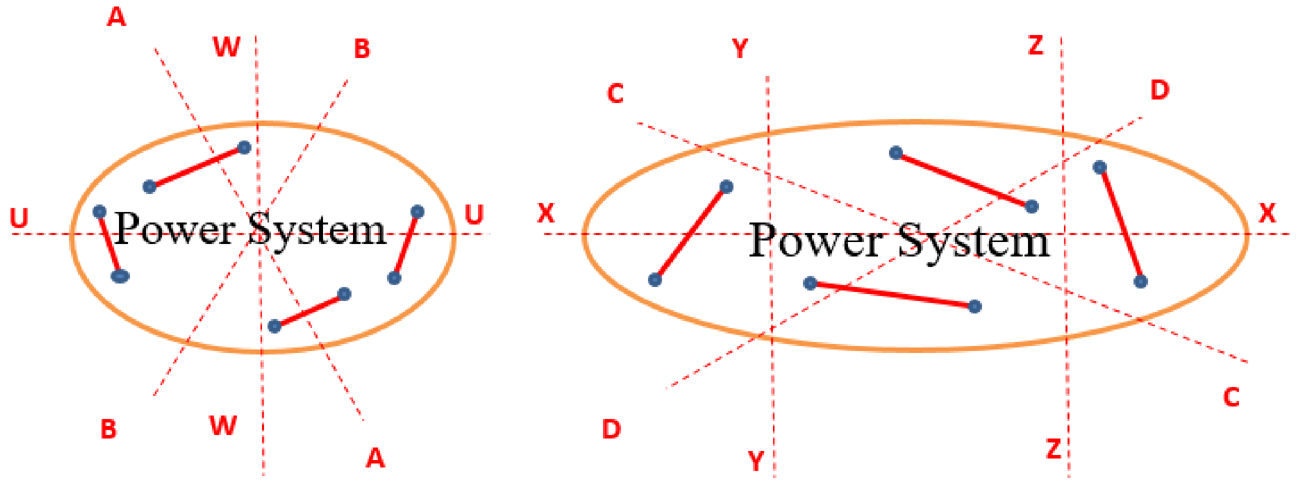



*Fig. 1. Simplified block diagram of an integral algorithm*

The third stage is shown as Block 3. It is a scheme of algorithm to determine (obtain) the output data for an optimizing mathematical model of capacity balances in emergency areas when the UFLS settings are engaged. There, calculations for the three basic modes are performed with the help of standard software. In particular, these calculations use a common mathematical model of the balance of active and reactive power system capacities to obtain the relevant power flows in the protection scheme for the maximum and minimum daily load modes and the mode of the maximum share of distributed generation.

Block 4 is dedicated to determining TLS: here, the calculations yield the set of UFLS devices (frequency relays) and the relevant amount of load capacity connected to them necessary for the most complete balancing of all affected areas of the power system's division for all versions of division considered at the second stage of the algorithm (Block 2). In order to do this, *a mathematical model of balancing the capacities in the emergency-divided power system* is used, which contribution is considered below in greater detail. Using the model allows for analyzing and increasing the efficiency of distribution and determination of the minimum total amount of balancing capacity of frequency load shed for all possible divisions of the power system. In fact, this process identifies a set of relays with non-zero (binary) integer use intensities that are most essential for load shedding. Concurrently, activation of other relays which do not coincide with the chosen ones in the optimal solution of the linear programming problem for this model is fairly improbable in any emergency situation. From the experience of using the algorithm in practice, this probability depends on the comprehensiveness of the power system division scenarios set developed at Stage 2 (Block 2). The obtained frequency appropriate for load shedding of a set of relays are then used to draw a table of analyzing modes and areas (Table 3).




– the transmission line cross-sections in the electric network;

– transmission lines which got into the cross-section.

*Fig. 2. Variants for arbitrary separation of the power system*

At the fifth stage (Block 5), analysis of calculations is performed according to Table 3, in particular, the lack or excess of load shedding is determined for every distribution network, every operator of the distribution network (ODN).

**Table 3. The fragment of the table the evaluation of TLS placement in the power system**

| Number of basic mode | Section of emergency | Number of region | Reserve of load shedding | | Total amount of load shedding in area | Amount of load shedding that was calculated |
|---|---|---|---|---|---|---|
| | | | MW | | MW | MW |
| 1 | 2 | 1 | 922 | | 1764 | 1662 |
| 1 | 3 | 2 | -146 | | 1080 | 1080 |
| 2 | 20 | 1 | 761 | | 2203 | 2101 |
| 1 | 17 | 1 | 637 | | 1895 | 1793 |
| 1 | 9 | 1 | 395 | | 1995 | 1995 |
| 3 | 14 | 2 | -19 | | 438 | 438 |
| 2 | 8 | 1 | 201 | | 2071 | 2071 |

**III. Mathematical model of capacity balance in an emergency-divided power system**

According to the described algorithm to solve the problem, the minimum required capacity is calculated by the formula

$$P^{LS}_{\tau,\,min} = \sum_{i=1}^{N_U} P_{i\tau} \cdot x_i^{opt}\,, \qquad (1)$$

where $\left\{x_i^{opt}\right\},\, i = \overline{1,\ldots,N_U}$ – is the set of optimal values of binary variables of device *i* usage or not usage to remedy the consequences of an arbitrary emergency which has led to frequency drop in a power system with a pre-determined set of power modes with measured capacities of load-shedding devices that determines the network distribution of used load-shedding capacity and is found as the solution of the problem of integer optimization that is to minimize the value of the function

$$\sum_{i=1}^{N_U} (1-k_i)\cdot x_i \;\rightarrow\; min \qquad (2)$$

if

$$\sum_{i=1}^{N_U} A_{ri} \cdot \left(P_{i\tau} - G_{i\tau}^{RES}\right) \cdot x_i \geq D_{r\tau} \Bigg|_{r=\overline{1, N_{R^-}}} \Bigg|_{\tau=\overline{1, N_T}} \quad ; (3)$$

where

$$\sum_{i=1}^{N_U} A_{ri} \cdot \left(P_{i\tau} - G_{i\tau}^{RES}\right) \cdot x_i \geq s \cdot P_{r\tau}^{cons} \Bigg|_{r=\overline{1, N_{R^+}}} \Bigg|_{\tau=\overline{1, N_T}} \quad , (4)$$

$A_{\text{ri}}$ is an element of the matrix of the affiliation of load-shedding devices (frequency relays) to the isolated areas: $A_{\text{ri}} = 1$, if the device *i* belongs to the isolated area *r* and $A_{\text{ri}} = 0$ if not;

$P_{i\tau}$ is the capacity of load connected to device *i* measured in regime $\tau$;

$G_{i\tau}^{RES}$ is the determined active power of renewable energy sources which provide capacity for points active in the area covered by device i in mode $\tau$;

$D_{r\tau}$ is the deficit of active capacity of area *r* in regime $\tau$, resulting from the division of the power system by an emergency followed with frequency drop;

*s* is the % of load that is set by the system operator to engage consumers in load shedding;

$P_{r\tau}^{cons}$ is the total active capacity load of the surplus region *r* in mode $\tau$;

$k_i$ is the consumer categorization factor / active setting for frequency of the consumer connected to device *i*;

$x_i$ is the sought binary variable of state of the device *i*: $\mathrm{x}_i = 1$, if device *i* is involved in unloading the power system;

$N_U$ is the number of unloading devices (relays) in the power system;

$N_{R^-}$ is the number of isolated areas of the power system deficit in active power;

$N_{R^+}$ is the number of isolated areas of the power system with surplus active power;

$N_T$ is the number of measurements on devices during the calculation period *T*.

**IV. An example**

A scheme of power system is shown on Fig. 3. It has two controlled crossings IV-IV and V-V which were disconnected resulting in respective emergency areas (Fig. 3). Besides that, we considered other, fairly different system divisions to demonstrate various cases of arbitrary emergency regions formation (1-1, 2-2, 3-3, 4-4). When the problem was solved according to the proposed algorithm, we obtained a Table of analysis of areas and modes (see the description of Stages 4 and 5 of the algorithm of TLS determination), a fragment of which is shown in Table 3.

If the described power system were required to follow the ENTSO-E policy requirements [5] for TLS, then no less than 45% load, +/- 7%, would have to be connected to UFLS. The minimum TLS should thus be 38%, while the maximum should be 52%.

However, Table 3 (lines 1 and 3) shows that after the deficits were covered, the remained 24% (1334 MW) and 33% (1758 MW) is less than the minimum required reserve of 38%. In the second line, the reserve was 39% (1423 MW), exceeding the minimum capacity required. Given these reserve values, it is possible to calculate the amount of consumer capacity in megawatts which requires load shedding in every isolated area, and, consequently, the TLS of the power system as a whole.

**V. Conclusions**

1. The analysis conducted in this study of large-scale power failures involving frequency drop and the properties of various types of operating reserve in power systems allows us to state that the system of automatic frequency load shedding is currently the only way to balance a power system in the event of large and sudden imbalances of active power regardless of their causes. An essential condition for the effective operation of the automated frequency load-shedding system is the sufficiency of amounts and expediency of capacity distribution of consumers connected to the system. Determination of sufficient load shed should be based solely on a comprehensive analysis of both the specifics of the power network structure and the power flow distribution for a sufficiently diverse set of power modes. This approach allows to obtain precise values of capacity deficit and the appropriate sources to address their recovery within the set of means of the available operating reserve.

2. In this paper, we propose a method and an algorithm to determine the appropriate capacity of the UFLS operating reserve, as well as a mathematical model for its optimal balancing considering the possible division of the power system into arbitrary electrically disconnected emergency areas. The application of these tools for evaluating and adjusting load shed substantially reduces the likelihood of

a total blackout in emergency areas due to complex cascading failures followed by significant frequency drops. The sequential algorithm of formal procedures to solve the problem, alongside the proposed specific data structures and mathematical model for balancing the emergency areas equip the maintenance services and control centers of power systems with a tool to precisely model and construct a UFLS system.

3. Using a real power system as an example, we proved,

quantitatively, that the value of the total load shed mandated by the current standards and regulatory documents in the applicable energy legislation is an insufficiently trustworthy parameter for defining the UFLS systems' basic properties. In order to determine the reasonable value of this parameter and the consequent distribution of load-shedding capacities in the system, it is necessary to use a toolkit for accurate calculation of the system's operational mode states. One such toolkit and a case of its implementation is proposed in our research.

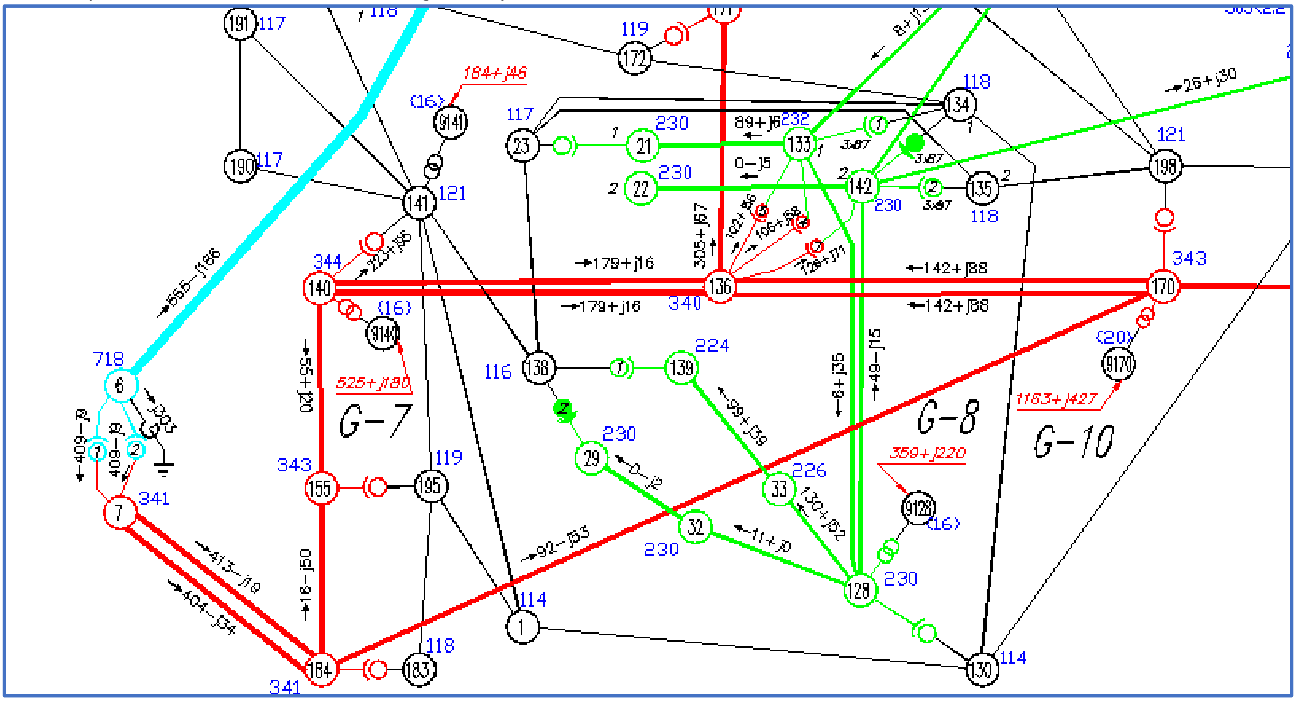



*Fig. 3. Single Line Diagram of Power System (fragment)*

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