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MATHEMATICAL AND COMPUTER MODELS FOR THE DETERMINATION OF CARRYING CAPACITY RESERVE IN POWER ELEMENTS OF POWER SUPPLY SYSTEMS

The paper analyzes and formalizes the notion of carrying capacity reserve in power elements of power supply system (PSS) with the consideration of all the conditions of the allowed operation of this element. There had been suggested the mathematical and computer models for processes of determination of reserve in carrying capacity of cable lines suitable for use in conditions for manufacturing expansion, modernization of technological process and switching new consumers of electric energy to the existing electricity supply network.

Key words*:reserve of carrying capacity, calculated load, acceptable operation mode of the PSS element, mathematical mode, passive and active restrictions, cable line.*

Introduction

Efficiency of capital investments in electric power supply systems is formed at the initial stages of their designing in the process of determination of electric loading of PSS power elements. The detraction of calculated electric loads may result in insufficient carrying capacity of PSS elements and their early failure; the overstating – in ungrounded increase in capital investments for their construction and worsening of electromagnetic compatibility of PSS elements. Realizing the importance of accurate prognostication of calculated load, methods of their determination are regulated since 1961 [1] and scientific works on improvement and specification of these methods remain actual up to now (see, for example [2 – 5]).

Since 1961 the wording of the normative document [1] has been amended and specified for several times, considering the new research of electric loading of PSS elements. Nowadays, the guiding technical materials [6] are the acting analogue of this document.

According to [6] the calculating is called the conventionally unchanged load of PSS element which is equivalent to the really changing in time load of this element as for maximum temperature of its heating.

As it is known, for different conductors in [7] maximum permissible current which corresponds to the long-term permissible heating temperature of the conductor is standerdized. The known calculating load of PSS element allows to apply these standardized current values for the case of changing in time load.

Close in meaning to the notion of calculated load is the notion of reserve of carrying ability of PSS power element. Unlike the contemporarily known works, dedicated to the creation of new and improvement of the existing methods for the determination of the calculating loads, this paper considers the task of determination of the reserves of carrying capacity PSS elements in the process of their operation. The notion of carrying capacity reserve does not currently have the formal generally accepted definition. This paper attempts to introduce the strict definition proceeding from intuitional understanding of carrying capacity reserve as the maximum possible loading value, which is possible to be conducted by PSS element above its existing load. It is shown that the methods for the determination of calculating load and determination of carrying capacity reserves of PSS elements may not be formally reduced to each other. If in the process of determination of calculating load of PSS power elements it is necessary to proceed from maximum allowed temperature of heating these elements, then determination of their carrying capacity requires to consider the other conditions of their operation.

Problem setting

In the operation process of electric power supply systems there may appear the necessity in the determination of the value of additional load, which the existing PSS element is able to carry. For the existing external feeding lines and distributional nets of electric energy consumers such a necessity may appear due to expansion of manufacturing, modernization of technological processes, switching the new consumers of electric energy etc. In such cases the evaluation of the reserves of carrying capacity in the electric mains is usually done as for the allowed current, regulated by ПУЕ [7], using the notion of carrying capacity reserve, by analogy with the notion of calculating load. Such an evaluation allows to ensure permissibility in heating the PSS element in case of increase in its load within the found reserve of carrying capacity, However, the permissibility in the mode of PSS element operation is determined not only by the condition of the permissible heating of this element in the normal operating mode. Its carrying capacity is also influenced by its heating in post-multifunction mode, considering the allowed overloading and capacity of consumption in this mode, loss of voltage in normal and post-mulfunction mode and other conditions. The results of researches, conducted by the authors, showed that neglecting these conditions may cause the significant failures in the evaluation of reserves of carrying capacity of PSS elements.

The above- mentioned shows that the intuitional understanding of the reserve of carrying capacity (RCC) of PSS element requires specification. This paper presents the formal definition of this notion and suggests mathematical and computer models for the determination of value of the reserve of carrying capacity of cable line following the experimental data on mode of its operation. It has been shown that in the processes of determination of RCC on the base of this model it is expedient to use the methods for solving tasks of linear programming, but the common algorithm of task solution must be supplemented due to specific peculiarities of the task set.

Main results

Further on the authors suggest to comprehend the reserve of carrying capacity of PSS element as the maximum possible value of full capacity $S_{3,}$ which is possible to be additionally carried by this element under condition of execution of all limitations, stipulating for permissibility of conditions of its operation.

Let us consider the peculiarities of the task for the determination of the reserve of carrying capacity of cable line (CL). The analysis shows that the execution of majority of conditions of the permissible operation of different PSS elements directly depends on value S_V. But there are conditions, execution of which does not depend on this value. Despite it, such conditions must also be considered in the process of determination of carrying capacity of PSS elements. For example, it is obvious, that the increase in CL load influences the execution of the condition for its additional heating, but it may exert no influence on execution of condition of permissible short-term heating in this line by short circuit current (SCC) if the value of SCC in the beginning of the line remains unchanged. The corresponding condition may be written as

$$k_{perm} \cdot I_{perm}(F) \geq I_p + \frac{S_V}{\sqrt{3} \cdot U}, \tag{1}$$

$$F \geq F_{SC} = \frac{I_{SC} \cdot \sqrt{t_l}}{C}, \tag{2}$$

where $k_{perm} = k_e k_l$ – factor of permissible load (specifies the value of the permissible current for specific conditions of line operation); k_e, k_l – factors of environment and laying correspondingly (consider the distinction of environmental parameters and laying conditions of the line form those accepted in REIA [1] during making up a table of permissible currents); $I_{perm}(F)$ – permissible current of CL cross-section being F in accordance with REIA, which corresponds to the existing load of this line calculated current of CL I_e; U – line voltage; F_{sc} – minimum section of the line on condition of thermal activity of SCC (is determined by standardized calculating methods for thermal activity of SCC); I_{sc}, t_g – current and given time of short circuit in the beginning of CL; C – standardized parameter, value of which depends on CL type.

Condition (1) is written for the case of equality of power factors of the existing calculating load of the line and its additional load S_3. Under these very conditions the additional load S_3 causes maximum increase in acting current value, and, correspondingly, the temperature of line heating. Since in the process of determination of the reserve of carrying capacity, the parameters of additional load (and, in particular, its power factor) may be unknown, we will further on proceed from this most unfavourable assumption.

We name the conditions of permissible operation of PSS element, the execution of which depends on the value S_3, as active in the task of determination of the reserve of carrying capacity of this element, and other conditions – as passive in this task. It is obvious that the condition (1) is an active one, and condition (2), written for the case of remote from the feeding source point of S.C., is passive one, since in this case its execution does not depend on value the S_3.

Requiring the execution of all conditions for the permissible operation of PSS element in the determination of value S_V, the authors proceeded from the following. The execution of passive conditions according to their definition, does not depend on value S_V. Therefore, if at least one passive condition shall not be executed, it means that the corresponding PSS element operates in impermissible conditions even without the increase in its load and is subject to change. If in such conditions we find the reserve of its carrying capacity, considering only the active conditions of the task, and it appears that $S_3 > 0$, it may mislead a person who will make a decision as for the permission for this element to operate after increase in its load. Increasing load of PSS element by value $\Delta S \le S_3$, we worsen the conditions of its operation, but the elements load remains permissible. If the existing conditions of PSS element's operation may be worsened, it's quite logical that prior to worsening they were also been permissible. However it is not so, since one of the passive conditions, as it had been accepted, was and will remain impermissible. To avoid such situation, it would be suggested to check both, active and passive conditions, in the process of the determination of the reserve of carrying capacity, and in case of non-execution at least of one passive condition, to consider that $S_3 = 0$. Considering the above- mentioned, the mathematical model for the determination of the reserve of carrying capacity of CL will be:

$$\mathrm{f}(S_v) = S_v \to \max_{S_V}, \tag{3}$$

$$k_{perm} \cdot I_{perm}(F) \ge I_p + \frac{S_V}{\sqrt{3} \cdot U}, \tag{4}$$

$$k_{a.b.} \cdot k_{perm} \cdot I_{perm}(F) \ge k_{i.a.b} \cdot k_{e.a.b} \cdot \left(I_r + \frac{S_v}{\sqrt{3} \cdot U} \right), \tag{5}$$

$$\frac{r_0(F) \cdot (P_r + S_v \cdot cos(\varphi)) + x_0(F) \cdot (Q_r + S_v \cdot sin(\varphi))}{10 \cdot U^2} \cdot L \le \Delta U_{n.perm}, \tag{6}$$

$$\frac{r_0(F) \cdot (P_r + S_v \cdot cos(\varphi)) + x_0(F) \cdot (Q_r + S_v \cdot sin(\varphi))}{10 \cdot U^2} \cdot L \cdot k_{i.a.b} \cdot k_{e.a.b} \le \Delta U_{a.b.perm}, \tag{7}$$

$$F \ge \frac{I_{SC} \cdot \sqrt{t_L}}{C}, \tag{8}$$

where $k_{a.b.}$ – factor of maximum allowed overloading in CL in post mulfunction mode according to REIA; $k_{i.a.b}$ – factor of load increase in the postmulfunction mode in CL (shows how many times the load increases in postmulfuntion operation mode of CL);k_{lab} – part of total load to be consumed in post malfunction mode of CL operation; P_r, Q_p – correspondingly active and reactive calculating capacities of CL;cos(φ) – capacity factor; $r_0(F)$, $x_0(F)$ – correspondingly the specific active and reactive resistance of the line with cross-section F; $\Delta U_{\text{n.rerm}}$, $\Delta U_{\text{ab.perm}}$ – permissible voltage loss in CL in normal and postmulfunction of line operation.

As it is seen , the peculiarity of the obtained mathematical model is availabity of both active (4) – (7) and passive conditions (8). If we neglect the passive condition, we receive the ordinary task of linear programming, in which the efficiency factor is the diagonal function f(S_{v}), controllable variable – value S_{v}, and conditions (4) – (7) act as limitations for controllable variable.

The executed by the authors analysis of tasks of determination of carrying capacity of other power PSS elements shows that the number of passive conditions may be greater.

Since the execution of passive conditions does not depend on value to be found, for the solution of the task set it is expedient to check the execution of all passive conditions (in this case condition (8)). If at least one passive condition dose not execute, the search for value S_3 makes no sense. In this case it is necessary to accept $S_{\text{v}} = 0$.

If all passive conditions are executed, it is necessary to solve task (3) – (7), for the determination of value S_3, using the known methods of linear programming.

As it is seen form mathematical model (3) – (8), for its solution it is necessary to know existing values of calculated current and capacity factor of CL. But it is impossible to measure these values directly, since the real load of cable line changes in time and calculated current, according to [6] is conditionally unchanged value, equivalent on maximum temperature of its heating.

Normative document [6] regulates the determination of calculated load fro elements in the electric power supply systems on the stage of their designing. In [8] the authors proved that the use of normative methods for the forecast of calculated load in the process of PSS operation is not expedient. In this paper the authors suggested mathematical and computer models for determination of existing calculated loads in the acting systems fro electric power supply following the experimental data, received by electronic meter within time, not less than the duration of maximum loaded shift of operation of electric energy consumer. The constant of PSS element heating, conducting this load is also considered. Using models, allow to find calculated current and capacity factor for any PSS element following the results of discrete data of change in active and reactive capacity with the set period of electric counter integration.

Fig. 1 shows the computer model for determination of the reserve of carrying capacity of all cable line by the obtained parameters I_{r} and cos(φ) for one of 10kW CL in Severinovka brick part.

	B–F	G	H–K
1	**Визначення запасу пропускної здатності КЛ**		
2	**Параметри КЛ**		
3	Переріз КЛ, мм^2		**Fкл** = 50
4	Активний питомий опір КЛ, Ом/км		**Ro** = 0,62
5	Реактивний питомий опір КЛ, Ом/км		**Xo** = 0,09
6	Допустимий струм КЛ за ПУЕ, А		**Iдоп** = 140
7	Довжина лінії, км		**L** = 3,1
8	**Дані нормального режиму**		
9	Напруга, кВ		**U** = 10
10	Повна розрахункова потужність, кВА		**Sp** = 1050,0
11	Розрахунковий струм КЛ, А		**Ip** = 60,6
12	Коефіцієнт потужності		**CosF** = 0,88
13	Активна розрахункова потужність, кВт		**Pp** = 924,0
14	Реактивна розрахункова потужність, квар		**Qp** = 498,7
15	Коефіцієнт допустимого навантаження		**Кдоп** = 0,9
16	Допустима втрата напруги в КЛ, %		**dUндоп** = 5
17	**Дані аварійного режиму**		
18	Струм к.з. на початку лінії, кА		**Iкз** = 3,200
19	Приведений час к.з., с		**tп** = 1,5
20	Тепловий коефіцієнт С, (А*с^(1/2))/мм^2		**C** = 90
21	Мінімальний переріз лінії за умовою к.з, мм^2		**Fкз** = 43,55
22	**Дані післяаварійного режиму**		
23	Коефіцієнт збільшення навантаження в п.а. режимі		**Кзпа** = 1,9
24	Макс. допустимий коефіцієнт навантаження в п.а. режимі		**Кпа** = 1,1
25	Частка навантаження у п.а. режимі		**Кнпа** = 0,8
26	Допустима втрата напруги в КЛ, %		**dUпадоп** = 5
27	**Запас пропуксної здатності, кВА, кВт, квар, А:**		
28	**Sз = 529,4 Рз = 465,8**		**Qз = 251,4 Iз = 30,6**
29			
30	**Виконання обмежень**		
31	**Активні обмеження**		
32	**Ip + Iз ≤ Кдоп*Iдоп**		**Допустимість нагрівання в н.р.**
33	91,18 ≤ 126		ДОП.
34	**Кз*(Ip+Iз)*кнпа) ≤ Кпа*Кдоп*Iдоп**		**Допустимість нагрівання в п.а.р.**
35	138,60 ≤ 138,60	v	ДОП.
36	**dUн% ≤ dUндоп**		**Допустимість втрат напруги в н.р.**
37	2,88 ≤ 5		ДОП.
38	**dUпа% ≤ dUпадоп**		**Допустимість втрат напруги в п.а.р.**
39	4,38 ≤ 5		ДОП.
40	**Пасивні обмеження**		
41	**Fкз ≤ Fкл**		**Допустимість термічної дії С.К.З.**
42	43,5 ≤ 50		ДОП.
43			**Точність фіксації обмежень: 0,50%**

Fig. 1. Computer model for determination of the reserve of carrying capacity

Computer model is created on the working sheet of electronic processor Excel as an electronic table and contains the initial data and results of calculation, received by the built-in software “Search and solution” in Excel, using the method for linear programming, realized in this software. The calls of electronic table also use formulas, shown in table 1. For convenient analysis of the results of task solution, the column G automatically fixes conditions, which restricted the value o parameter S_v. The accuracy in fixation of restrictions is set in the cell К43.

If CL does not satisfy the passive restriction, or at least one active restriction when $S_3 = 0$, than in cell B29 automatically appears the information “ Existing cross-section of CL does not satisfy the restrictions. Sv = 0!”

Table 1.

Formulas of electronic table of computer model for the determination of the reserve of carrying capacity of CL

Cells	Formulas of working sheet in Excel
K11	=Sp/КОРЕНЬ(3)/U
K13	=Sp*CosF
K14	=Sp*SIN(ACOS(CosF))
K21	=Iкз*КОРЕНЬ(tп)*1000/C
F28	=Sз*CosF
I28	=Sз*SIN(ACOS(CosF))
K28	=Sз/КОРЕНЬ(3)/U
B29	=ЕСЛИ(И(H33="ДОП."; H35="ДОП."; H37="ДОП."; H39="ДОП."; H42="ДОП."); ""; "Існуючий переріз КЛ НЕ задовольняє обмеженням. Sз = 0!")
C33	=Ip+Iз
E33	=ЕСЛИ(ИЛИ(Кдоп = ""; Iдоп = ""); ""; Кдоп*Iдоп)
H33	=ЕСЛИ(C33 <= E33 + C33*0,00001; "ДОП."; "НЕ ДОП.")
C35	=ЕСЛИ(Кз > 1; Кз*(Ip+Iз)*kнпа; 0)
E35	= Кпа*Кдоп*Iдоп
H35	=ЕСЛИ(C33 <= E33 + C33*K43; "ДОП."; "НЕ ДОП.")
C37	=ЕСЛИ(U = ""; ""; (Ro*(Pp+Pз)+Xo*(Qp+Qз))*L/10/U^2)
E37	=dUндоп
H37	=ЕСЛИ(C35 <= E35 + C35*K43; "ДОП."; "НЕ ДОП.")
C39	= ЕСЛИ(Кз > 1; dUн*Кз*kнпа; 0)
E39	=dUпадоп
H39	=ЕСЛИ(C39 <= E39 + C39*K43; "ДОП."; "НЕ ДОП.")
C42	=Fкз
E42	=Fкл
H42	=ЕСЛИ(C42 <= E42 + C42*K43; "ДОП."; "НЕ ДОП.")
G33	=ЕСЛИ(И(C33 <= E33 + C33*K43; C33 >= E33 - C33*K43); "v"; "")
G35	=ЕСЛИ(И(C35 <= E35 + C35*K43; C35 >= E35 - C35*K43); "v"; "")
G37	=ЕСЛИ(И(C37 <= E37 + C37*K43; C37 >= E37 - C37*K43); "v"; "")
G39	=ЕСЛИ(И(C39 <= E39 + C39*K43; C39 >= E39 - C39*K43); "v"; "")
G42	=ЕСЛИ(И(C42 <= E42 + C42*K43; C42 >= E42 - C42*K43); "v"; "")

Conclusions

The paper formalizes the notion of the reserve of carrying capacity of power element of the electric energy supply system with the consideration of all conditions of the permissible operation of this element. There had been suggested the mathematical and computer models for the processes of determination of the reserve of carrying capacity in cable lines, fit for use in conditions of expansion of enterprise, modernization of technological process and switching new consumers of electric energy to the existing electric power net. The operability of the suggested models had been tested in real data of existing system of electric energy supply during the solution of the question on the permissibility in switching additional loads to the existing CL 10 кV.

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