ANNALS OF FACULTY ENGINEERING HUNEDOARA
– INTERNATIONAL JOURNAL OF ENGINEERING
Tome X (Year 2012) – FASCICULE 3 (ISSN 1584 – 2673)

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THE SIZING OF THE BRANCH THREE-PHASE LOW VOLTAGE POWER LINES THROUGH SUPERPOSITION METHOD

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ABSTRACT: *Traditionally, the main and branch three-phase distribution lines are dimensioned by the minimum conductor-material volume method or that of the moments method. The paper introduces a new method of designing the power distribution lines. Its advantage consists in the fact that it is simple and easy to apply. It is based on the superposition method used in solving the three-phase electric circuits.*
KEYWORDS: *sizing, three-phase distribution lines, superposition method*

INTRODUCTION

Usually, the branch three-phase low voltage distribution power lines can be size by the admissible maximum voltage drop method, the minimum conductor material volume method and the moments' method [1,2,3,4]. These methods can be use easy, when is not necessary the admissible maximum current correction by a specify cross-section, depending on duty type of the consumer. If is necessary to use this correction, the sizing of the branch three-phase power lines is made simple, through superposition method propose in this paper. This method consists in compute of simple power lines cross-section that composes the complex branch power lines through the admissible maximum voltage drop method. For the common cross-section lines, these are compute like sum of the determinate cross-section for every line partly.

The paper gives an example of sizing the branch three-phase low voltage power lines through superposition method.

METHODOLOGY. THE SIZING OF THE BRANCH THREE-PHASE POWER LINES THROUGH SUPERPOSITION METHOD

It is consider the general case for a simple branch power line (fig.1) that supplies n three-phase inductions motors. Each motor works in intermittent periodical duty with the different relative duty cycles, DA_i (i = 1,2,…,n). These motors have the powers P_{ci}[W] (i = 1,2,…,n).
First time, is calculate the currents I_{ci} [A] for every n motors:

$$I_{ci} = \frac{P_{ci}}{\sqrt{3} \cdot U_{ln} \cdot \eta_{ci} \cdot \cos\varphi_{ci}} \ [A] \tag{1}$$

In this relation U_{ln} [V] is the line rated voltage, η_{ci} [-] is the efficiency, and $\cos\varphi_{ci}$ [-] is the power factor for every motors.

The branch line is decomposing in n simple branch lines (fig.2), every line will be calculated with the admissible maximum voltage drop method. The lengths L_i of the simple lines, in that case, become:

$$L_i = l_o + l_i, \ i = 1,2,\ldots,n \tag{2}$$

Will be size the simple lines from fig.2 that compose the branch line from fig.1. For this reason it is approximate compute the reactive voltage drop for every line:

$$\Delta U_{lri} = \sqrt{3} \cdot X_i \cdot I_{ci} \sqrt{1-\cos^2\varphi_{ci}} \ [V], i=1,2,\ldots,n \tag{3}$$

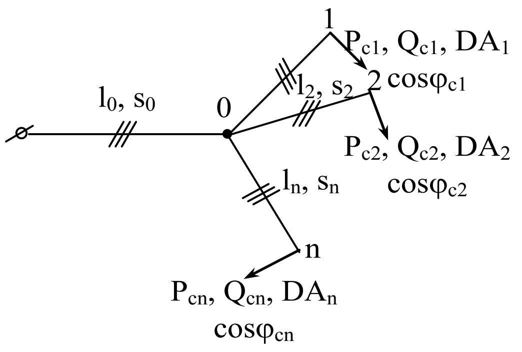

Figure.1 The branch three-phase power lines that feeds with electric energy n consumers

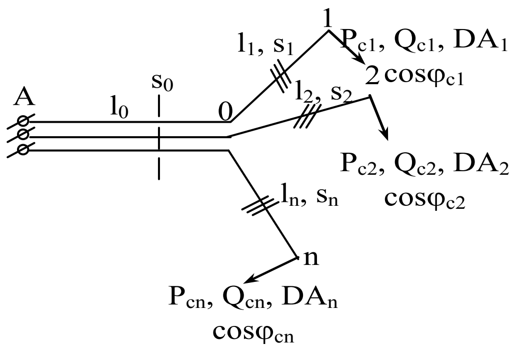

Figure.2 Decomposition of the branch three-phase power lines from figure 1 in n simple power lines

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The reactances X_i [Ω] for every simple line are compute with:

$$X_i = 2\pi \cdot f \cdot L_{01} \cdot (l_o + l_i) \tag{4}$$

In this relation L_{01} [H/m] is the specific line inductance, for underground cable, in the first phase it is calculated with [1]:

$$L_{01} = (2.6\ldots3.2)\cdot 10^{-7}\ \text{[H/m], for underground cable with } U_{ln} \leq 15\ \text{kV}$$
$$L_{01} = (3.2\ldots3.9)\cdot 10^{-7}\ \text{[H/m], for underground cable with } U_{ln} > 15\ \text{kV} \tag{5}$$

For overhead line the specify reactance is estimate with: $X_{01} = 0.4 \cdot 10^{-3}$ [Ω/m].

In this case:

$$X_i = X_{01} \cdot (l_o + l_i)[\Omega]\ i = 1,2,\ldots,n \tag{6}$$

The total active voltage drop for n simple lines, it is calculate with:

$$\Delta U_{l\,max} = \frac{\Delta U_l[\%]}{100} \cdot U_{ln}\ [V] \tag{7}$$

For motors $\Delta U_l[\%] = 5$.

Now it computes the active voltage drops for n simple lines:

$$\Delta U_{lai} = \Delta U_{l\,max} - \Delta U_{lri}\ [V]\ i = 1\ldots n \tag{8}$$

Using the admissible maximum voltage criterion, the simple three-phase cross-sections are calculated with:

$$s_i = \frac{\sqrt{3} \cdot \rho \cdot I_{ci} \cdot \cos\varphi_{ci}}{\Delta U_{lai}} \cdot (l_o + l_i) \tag{9}$$

Afterwards, it is choose for lines normalized cross-sections s_{ni}, by an immediate superior value ($s_{ni} \geq s_i$).

The choose cross-sections are further performed to warm check of the conductors. For this, the admissible maximum current I_{max} [A] from the tables [3,5], depending on real temperature θ_{02}[°C] and on duty cycle of the motor:

$$I'_{max} = c_\theta \cdot c_l \cdot I_{max} \tag{10}$$

The temperature correction coefficient c_θ of admissible maximum current is calculated with [4]:

$$c_\theta = \sqrt{\frac{\theta_{max} - \theta_{02}}{\theta_{max} - \theta_{01}}} \tag{11}$$

Here, θ_{max} [°C] is the admissible maximum temperature of conductor insulation, and θ_{01}[°C] is temperature for the maximum value of current I_{max}.

The correction coefficient c_l of maximum current depending on duty cycle and it is calculated with [3]:

$$c_l = \frac{0.875}{\sqrt{DA}};\ c_l = 0.875 \cdot \sqrt{\frac{t_c}{t_f}} \tag{12}$$

The relative duty cycle DA it is compute with:

$$DA = \frac{t_f}{t_f + t_p};\ DA = \frac{t_f}{t_c} \tag{13}$$

where t_f[s] is a work time of motor, t_p[s] is pause time of motor and t_c[s] is cycle time:

$$t_c = t_f + t_p \tag{14}$$

The motors feed with electric energy through branch line work in intermittent periodical duty if the maximum time cycle is by 10 minutes and the work time of motor is by 4 minutes. For copper conductors with cross-sections under 10 [mm^2] and for aluminium conductors with cross-section under 16 [mm^2], c_l=1 both in intermittent periodical duty and in permanent duty.

The line cross-sections will not warm, if are valid the relations:

$$I_{ci} \leq I_{max\,i},\ i = 1,2,\ldots,n \tag{15}$$

After will find the normalized cross-sections s_{ni}, $i = 1,2,\ldots,n$ of simple three-phase line, it can be calculating the main cross-section line:

$$s_O = s_{n1} + s_{n2} + \ldots + s_{nn};\ s_o = \sum_{i=1}^{n} s_{ni} \tag{16}$$

After that, are calculate the voltage drop when the motors are start for the line from fig.1. It is consider that one motors start and the other work at rated values. These voltage drops are calculated with:

$$\Delta U_{p1} = \sqrt{3}\Big[R_{010} \cdot l_o \cdot \Big(k_{p1} \cdot I_{c1} \cdot \cos\varphi_{c1} + \sum_{i=2}^{n} I_{ci} \cdot \cos\varphi_{ci} \Big) + R_{011} \cdot l_1 \cdot k_{p1} \cdot I_{c1} \cdot \cos\varphi_{c1} + X_{010} \cdot l_o \cdot \Big(k_{p1} \cdot I_{c1} \cdot \sin\varphi_{c1} + \sum_{i=2}^{n} I_{ci} \cdot \sin\varphi_{ci} \Big) + X_{011} \cdot l_1 \cdot k_{p1} \cdot I_{c1} \cdot \sin\varphi_{c1} \Big] \quad (17)$$

$$\Delta U_{p2} = \sqrt{3}\Big[R_{010} \cdot l_o \cdot \Big(I_{c1} \cdot \cos\varphi_{c1} + k_{p2} \cdot I_{c2} \cdot \cos\varphi_{c} + \sum_{i=3}^{n} I_{ci} \cdot \cos\varphi_{ci} \Big) + R_{012} \cdot l_2 \cdot k_{p2} \cdot I_{c2} \cdot \cos\varphi_{c2} + X_{010} \cdot l_o \cdot \Big(I_{c1} \cdot \sin\varphi_{c1} + k_{p2} \cdot I_{c2} \cdot \sin\varphi_{c2} + \sum_{i=3}^{n} I_{ci} \cdot \sin\varphi_{ci} \Big) + X_{012} \cdot l_2 \cdot k_{p2} \cdot I_{c2} \cdot \sin\varphi_{c2} \Big] \quad (18)$$

...

$$\Delta U_{pn} = \sqrt{3}\Big[R_{010} \cdot l_o \cdot \Big(k_{pn} \cdot I_{cn} \cdot \cos\varphi_{cn} + \sum_{i=1}^{n-1} I_{ci} \cdot \cos\varphi_{ci} \Big) + R_{01n} \cdot l_n \cdot k_{pn} \cdot I_{cn} \cdot \cos\varphi_{cn} + X_{010} \cdot l_o \cdot \Big(k_{pn} \cdot I_{cn} \cdot \sin\varphi_{cn} + \sum_{i=1}^{n-1} I_{ci} \cdot \sin\varphi_{ci} \Big) + X_{01n} \cdot l_n \cdot k_{pn} \cdot I_{cn} \cdot \sin\varphi_{cn} \Big] \quad (19)$$

The cross-sections have been chosen, when are true the relations:

$$\Delta U_{pi} \le \Delta U_{pmax} = \frac{12}{100} U_{ln} \quad (i=1,2,...,n) \quad (20)$$

In relations (17), (18), (19), R_{010}, R_{011}, ..., R_{01n}, X_{010}, X_{011}, ..., X_{01n} are the specific resistances and reactances for main line and for the lines with cross-sections s_{no}, s_{n1}, s_{n2}, ..., s_{nn}. Can be determining with accuracy the voltage drops on branch simple line when the motor works at rated values:

$$\Delta U_{l1} = \sqrt{3} \cdot \Big(R_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \cos\varphi_{ci} + R_{011} \cdot l_1 \cdot I_{c1} \cdot \cos\varphi_{c1} + + X_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \sin\varphi_{ci} + X_{011} \cdot l_1 \cdot I_{c1} \cdot \sin\varphi_{c1} \Big) \quad (21)$$

$$\Delta U_{l2} = \sqrt{3} \cdot \Big(R_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \cos\varphi_{ci} + R_{012} \cdot l_2 \cdot I_{c2} \cdot \cos\varphi_{c2} + + X_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \sin\varphi_{ci} + X_{012} \cdot l_2 \cdot I_{c2} \cdot \sin\varphi_{c2} \Big) \quad (22)$$

...

$$\Delta U_{ln} = \sqrt{3} \cdot \Big(R_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \cos\varphi_{ci} + R_{01n} \cdot l_n \cdot I_{cn} \cdot \cos\varphi_{cn} + + X_{010} \cdot l_o \cdot \sum_{i=1}^{n} I_{ci} \cdot \sin\varphi_{ci} + X_{01n} \cdot l_n \cdot I_{cn} \cdot \sin\varphi_{cn} \Big) \quad (23)$$

In these relations:

$$\sin\varphi_{ci} = \sqrt{1-\cos^2\varphi_{ci}}, \; i=1,2,...,n \quad (24)$$

These voltage drops are calculate on the following ways $l_o - l_1$ (21), $l_o - l_2$ (22) and $l_o - l_n$ (23). The calculate voltage drops with relations (21), (22), (23) must be under admissible maximum voltage from (7).

DISCUSSION. EXAMPLE OF SIZING THE BRANCH THREE-PHASE POWER LINES WITH SUPERPOSITION METHOD

It is supposed the size of the branch three-phase power line (presented in fig.1) made from appearance cable with plastic insulator that has copper conductors (ρ=0.017 Ω·mm²/m), through feed three motors (three-phase inductions motors M_1, M_2, and M_3), that work in intermittent periodical duty (t_{f1} = 200s, t_{c1} = 420s, t_{f2} = 180s, t_{c2} = 460s, t_{f3} = 230s, t_{c3} = 560s), which characteristics are present in table 1. In the same table gives the relative duty cycle for these three motors determine with relation (13).

The medium temperature that are place the line is θ_{02} = =+16 °C (θ_{max} = 70 °C). The line parts have the following lengths l_o = 30 m, l_1 = 60 m, l_2 = 50 m, and l_3 = 70 m. The admissible maximum currents for different cross-sections on warm criterion are presented in table 2.

Table 2: The admissible maximum currents for different cross-sections, for copper appearance cable, with plastic isolation at θ_{01} = +25 °C temperature

s[mm²]	2.5	4	6	10	16	25	35	50	70	95	120	150
I_{max}[A]	25	34	44	60	80	105	130	160	200	245	285	325

For the line sizing are use data from table 3. The compute results of main line through superposition method are present in tables 4.a, b, c and d.

Table 3: The specify values resistors and reactances for copper armoured cable, up to 1kV

s[mm²]	2.5	4	6	10	16	25	35
R_{01i}[Ω/km]	7.54	4.71	3.14	1.88	1.17	0.75	0.53
X_{01i}[Ω/km]	0.098	0.095	0.090	0.073	0.068	0.066	0.064

s[mm²]	50	70	95	120	150	185	240
R_{01i}[Ω/km]	0.37	0.26	0.198	0.157	0.125	0.101	0.078
X_{01i}[Ω/km]	0.063	0.06	0.060	0.059	0.058	0.056	0.054

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Table 4.a

Com-pute values	I_{ci} [A] (1)	l_o+l_i [m] (2)	ΔU_{lri} [V] (3)	X_L [Ω] (4)	L_{01} [H/m] (5)	ΔU_{lmax} [V] (7)	ΔU_{lai} [V] (8)	s_i [mm^2] (9)	s_{ni} [mm^2]	s_o [mm^2]
1	73.05	90	0.48	0.0074	$2.61 \cdot 10^{-7}$	19	18.52	8.94	10	20
2	30.65	80	0.19	0.0066			18.81	3.24	4	
3	37.37	100	0.28	0.0082			18.72	4.97	6	

Table 4.b

	c_0 [-] (11)	c_L [-] (12)	I_{maxi} [A] (Table 2)	I'_{maxi} [A] (10)	s_{ni} chose [mm^2]
0	1.095	1.325	105	152.34	25
1		1.268	60	83.34	10
2		1.400	34	37.25	4
3		1.365	44	48.2	6

Tabel 4.c

Computer values	ΔU_{pmax}[V] (20)	ΔU_{pi} [V] (17),(18),(19)	$\sin\varphi_{ci}$ [-] (24)	R_{01i} [Ω/km] table 3	X_{01i} [Ω/km] table 3	R_{010} [Ω/km] table 3	X_{010} [Ω/km] table 3
1	45.6	110.48	0.519	1.88	0.073	0.75	0.066
2		96.44	0.535	4.71	0.095		
3		98.41	0.535	3.14	0.09		

Table 4.d

Computer values	s_{n1} [mm^2]	s_{n2} [mm^2]	s_{n3} [mm^2]	s_{no} [mm^2]	R_{01i} [Ω/km] table 3	X_{01i} [Ω/km] table 3	ΔU_{pi} [V] (17)...(19)	ΔU_l [V] (21)...(23)
	Increase until the inequality (20) is true							
0	35	10	16	50	0.37	0.063	-	-
1					0.53	0.064	36.4	6.24
2					1.88	0.073	40.2	6.87
3					1.17	0.068	39.1	7.19

To compute the line voltage drop when the motors starting, the equations system (17), (18), (19), was simplify for the branch line that feeds with electric energy three motors.

From table 4.a for cross-sections: s_{no} = 25 mm^2, s_{n1} = 10 mm^2, s_{n2} = 4 mm^2, and s_{n3} = 6 mm^2, the voltage drops when motors M_2 and M_3 are starting, overtakes the admissible maximum values. These cross-sections increase step by step until the inequality (20) is true.

The final values of branch line cross-sections are present in table 4.d. For these cross-sections, with relations (21),(22),(23) (that was simplify for branch power line with three lines), was compute the total voltage drops when the motors work at rated values. These are smaller than admissible maximum voltage drop ΔU_{lmax} = 19 V.

CONCLUSIONS

The superposition method use to sizing the branch three-phase power lines is to decomposition the lines in a number of simple lines that are equal with the consumer number that are feed with electric energy. This method it is simple and easy to apply and it is useful to sizing lines that are supply motors that work in intermittent periodical duty. The superposition method is an economical sizing for electric power lines. This method may be applied, also, to sizing complex three-phase power lines with different configuration: the branches, the mains, the complexes, the lines that are supply from two or many feed point, and so on.

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