Analysis of the influence of non-sinusoidal and unbalanced network modes on induction motors

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Abstract. The parameters of electrical network modes do not correspond the requirements GOST 32144-2013 of Russian and the National technical regulation of Vietnam. In real operating conditions in electrical networks in non-sinusoidal and unbalanced modes there are harmonic components of voltages and currents as well as voltages and currents of negative sequence. They cause additional losses of active power, which leads to additional heating and causes premature aging of the insulation, and as the result, the reduction in the service life of induction motors. Currently, we see that the process of formation of intelligent electrical power systems is underway. Systems for continuous monitoring of power quality indices and parameters of electrical systems modes are being developed. These systems can be supplemented with programs for calculating characteristics that issue the warning when the unfavorable influence of the parameters of non-sinusoidal and unbalanced modes is detected on various electrical equipment of both electrical power systems and consumers of electrical energy. The paper provides an overview of the characteristics used to analyze, assess and predict the influence of poor power quality associated with non-sinusoidal and unbalanced of currents and voltages on induction motors. A computer program was developed to calculate these characteristics. The program was used to study the influence of non-sinusoidal and unbalanced modes on the induction motors of the coal sorting plant of the Vietnamese company “Cua Ong-Vinacomin”.

1 Introduction

The study of the influence of the parameters of non-sinusoidal and unbalanced modes on induction motors has been engaged in for a long time, since induction motors are the most used electrical equipment [1-11]. A special standard specifies the operating conditions for induction motors with unbalanced voltages [12]. They continue to fail due to damage despite many years of ongoing research on the influence of poor power quality on induction motors. For example, in April 2017, due to the poor power quality the induction motor failed at the “Alexandrovsky Mine” enrichment plant in the Trans-Baikal Territory [13]. Another 17 induction motors failed at water supply facilities and in the boiler house in the Trans-Baikal Territory in December 2017 [14]. Non-sinusoidal and unbalanced modes occur very often in electrical networks in Russia [15]. Poor power quality exists in coal mining areas in Vietnam [16]. This paper provides the overview of the characteristics used in special works to analyze, assess and predict the influence of poor power quality associated with non-sinusoidal and unbalanced of currents and voltages on induction motors. The computer program “Predicting the influence of non-sinusoidal unbalanced voltage on an induction motor” based on Microsoft Excel and Matlab was developed to calculate these characteristics. The program was used to study the influence of non-sinusoidal and unbalanced voltages on induction motors of the coal sorting plant of the Vietnamese company “Cua Ong-Vinacomin”. At present, intelligent electrical power systems are being created equipped with systems for continuous monitoring of mode parameters and power quality indices. They can be supplemented with programs for calculating characteristics that signal the influence of non-sinusoidal and unbalanced voltages and currents on the electrical equipment of electrical power systems and consumers of electrical energy.

2 Additional losses of active power in the induction motor in non-sinusoidal and unbalanced network modes

Non-sinusoidal and unbalanced voltages applied to the stator winding of the induction motor cause non-sinusoidal and unbalanced currents in the motor windings. They cause additional losses of active power. Fig. 1 presents the diagram of additional active power losses at non-sinusoidal and unbalanced voltages in the motor.

3 Assessment of the influence of non-sinusoidal voltage on the induction motor

The non-sinusoidal voltage leads to the increase in the active resistance to harmonic currents since at increased

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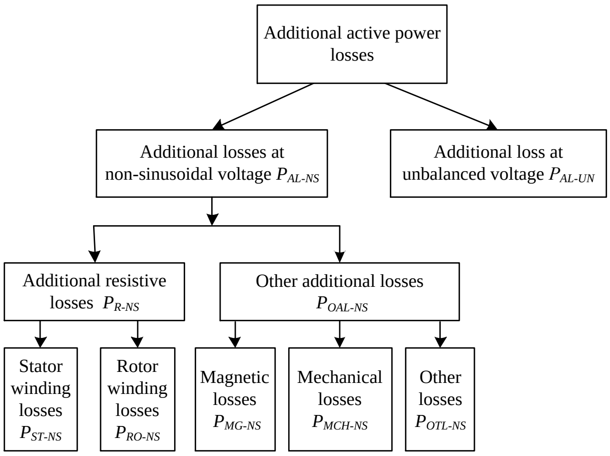

Fig. 1. Classification of active power losses in induction motor.

frequencies a skin effect appears in the stator and rotor windings. As a result, additional losses of active power appear in the induction motor, which cause heating. Additional losses at non-sinusoidal voltage consist of additional losses in the stator (P_{ST-NS}) and rotor (P_{RO-NS}) windings, which form additional resistive losses (P_{R-NS}). Other additional losses (P_{OAL-NS}) also occur in the induction motor with non-sinusoidal voltage, which are divided into magnetic (P_{MG-NS}), mechanical (P_{MCH-NS}) and other (P_{OTL-NS}). Magnetic losses are losses in the steel of the stator and rotor for hysteresis and eddy currents arising from magnetization reversal. Mechanical losses are friction losses in bearings and friction of the rotor against air. Mechanical losses are neglected as they have little influence on motor heating. There are also additional losses that are caused by the action of harmonics of magnetomotive forces, pulsation of magnetic induction in the teeth. These additional losses are taken equal to 1% of the rated power, are taken into account and added to the losses in the rotor winding [3].

Additional resistive losses (P_{R-NS}) are calculated according to [2, 4, 6] as

$$P_{R-NS} = K_R \sum_{n=2}^{50} \left[\left(K_{U(n)} / n \right)^2 \left(\sqrt{n} R_{ST-S} + \sqrt{n-1} R_{RO-S} \right) \right], \quad (1)$$

where K_R – the resistive loss coefficient in sinusoidal mode. The resistive loss coefficient is calculated by the expression

$$K_R = P_{R-S} U_1^2 / \left(U_N^2 Z^2 \left(R_{ST-S} + R_{RO-S} \right) \right), \quad (2)$$

where

$$Z = \frac{\sqrt{\left(X_{ST-S} + X_{RO-S} \right)^2}}{\sqrt{\left(R_{ST-S} + R_{RO-S} / s_N \right)^2 + \left(X_{ST-S} + X_{RO-S} \right)^2}}, \text{ p.u.};$$

P_{R-S} – the resistive losses in the windings of both the stator and the rotor of the induction motor in sinusoidal mode, which are calculated according to [17]; U_1 – the phase voltage of the fundamental frequency; U_N – the rated voltage; P_{ST-S}, P_{RO-S} – resistances of the stator and rotor windings in sinusoidal mode, Ohm; X_{ST-S}, X_{RO-S} inductances of stator and rotor windings in sinusoidal mode, Ohm.

Other additional losses (P_{OAL-NS}) are determined by the expression from [2, 4, 6] as

$$P_{OAL-NS} = P_{R-S} U_1^2 / \left(U_1 / U_N \right)^2 \sum_{n=2}^{50} \left[\left(K_{U(n)} / 100 \right)^2 n^{-0.6} \right]. \quad (3)$$

Total additional losses in non-sinusoidal mode

$$P_{AL-NS} = P_{R-NS} + P_{OAL-NS}. \quad (4)$$

The actual service life of the induction motor, i.e. the service life at non-sinusoidal voltage (T_{ASL-NS}) is calculated as

$$T_{ASL-NS} = T_{SSL} e^{-(E/K)\Delta T_{NS} / T_2 \left(T_2 + \Delta T_{NS} \right)}, \quad (5)$$

where E – the activation energy equal to $1.7622 \cdot 10^{-19}$ J; K – the Boltzmann constant equal to $1.38 \cdot 10^{-23}$J/K; $T_2 = \left(\Delta T_N + T_{amb} \right) + 273$ – the rated temperature of the hottest point of the motor, K; ΔT_N – the standard temperature rise of the winding over the ambient temperature, °C; T_{amb} – the ambient temperature, °C. The additional temperature rise of the induction motor over the ambient temperature (ΔT_{NS}) in non-sinusoidal mode is calculated as

$$\Delta T_{NS} \approx \Delta T_N P_{AL-NS} / P_S, \quad (6)$$

where $P_S = P_1 - P_N = P_{R-S} + P_{OAL-S}$ – the total losses of the induction motor in sinusoidal mode; P_1 – power consumption at the induction motor input, which is defined as $P_1 = P_N / \eta_N$ [17]; P_N – the rated power of the motor (net power at the output of the motor); η_N – the efficiency at rated power mode.

Efficiency of the induction motor in non-sinusoidal mode

$$\eta_{NS} = P_N / \left(P_1 + P_{AL-NS} \right). \quad (7)$$

Change in efficiency caused by non-sinusoidal voltage

$$\Delta\eta = \eta_N - \eta_{NS}. \quad (8)$$

4 Assessment of the influence of unbalanced voltage on the induction motor

In [1, 3, 5] it is noted that the resistance of the negative sequence of induction motors is 5-8 times less than the resistance of the positive sequence. Therefore, the voltage unbalance of 1% already creates the unbalance of currents in the windings of 7-9%. It is also indicated that at the value of the negative sequence voltage equal to 4% of the nominal, the service life of the induction motor is halved. When negative sequence currents flow, additional active power losses occur. Negative sequence currents cause additional heating, reduce the useful torque and available power of the induction motor. To assess the influence of unbalanced voltage on the induction motor, the parameters presented below are used.

When calculating additional active power losses [P_{AL-UB}] in unbalanced mode, it is assumed that they are proportional to the losses in the stator winding at the rated current of the fundamental frequency and do not depend on the motor load [3]. Additional power losses are determined by the expression

$$P_{AL-UB} = 2.41 P_{ST-S} K_{IL}^2 K_{2U}^2, \quad (9)$$

where $P_{ST\text{-}S}$ – the active power losses in the stator winding in symmetrical mode at the rated current of the fundamental frequency; K_{IL} – the locked-rotor current ratio at rated voltage; K_{2U} – the negative sequence voltage unbalance coefficient.

Losses of active power in the stator winding at nominal conditions are determined in [17] as

$$P_{ST\text{-}S} = 3I_N^2 R_{ST\text{-}S}\,, \qquad (10)$$

where I_N – the rated phase current of the stator of the motor; $R_{ST\text{-}S}$ - the resistance of the stator at rated power mode.

The real service life of the induction motor in unbalanced mode is defined in [3] as

$$T_{ASL\text{-}UN} = T_{SSL} / e^{\Delta T_{UB}}\,, \qquad (11)$$

where T_{SSL} – the standard service life, years; ΔT_{UB} – temperature rise of induction motor windings in unbalanced mode, °C; b – the coefficient characterizing the insulation of the induction motor [18], $°C^{-1}$. The temperature rise of the windings in unbalanced mode is defined in [3] as

$$\Delta T_{UB} = 434 K_{2U}^2 / b\,. \qquad (12)$$

Efficiency in unbalanced mode is

$$\eta_{UB} = \frac{P_N}{P_1 + P_{AL\text{-}UB}}\,, \qquad (13)$$

where $P_{AL\text{-}UB}$ – the additional losses in the induction motor in unbalanced mode.

Change in the coefficient of efficiency caused by unbalanced voltage

$$\Delta\eta = \eta_N - \eta_{UB}\,. \qquad (14)$$

The above characteristics are calculated using the computer program and are presented below.

5 The results of the analysis of the measured indices of the power quality in the power supply system of the coal sorting plant of the company "Cua Ong-Vinacomin"

Below are the results of measurements of indices of the power quality associated with non-sinusoidal and unbalanced modes, which affect the operation of induction motors. Tables 1-3 present the results of the analysis of the measured total harmonic distortion (K_U), the indices of the *n*-th harmonic component of the voltage ($K_{U(n)}$), the indices of the *n*-th harmonic component of the current ($K_{I(n)}$), the negative sequence voltage unbalance index (K_{2U}). The standard values for the indices are set at [19, 20]. The value of the measured $K_{U(n)}$) should not exceed 3%, and $K_{I(n)}$ 12%. Values that do not meet regulatory requirements are shown in bold in the tables. It can be seen from the tables that the voltage is non-sinusoidal at the node for connecting the electrical network of the plant to the supply network, since K_U is more than two times higher than the standard value. The indeces $K_{U(n)}$ and $K_{I(n)}$ are also significant. The K_{2U} value is much less than the standard value, therefore the voltage unbalance is insignificant.

Table 1. Measured K_U, K_{2U}, and their standard values.

Parameter	Phase A	Phase B	Phase C
K_{Umax}, %	**16,8**	**15,3**	**17,1**
K_{Ustand}, %	≤ 6,5		
K_{2Umax}, %	0.44		
$K_{2Ustand}$, %	5.0		

Table 2. Measured $K_{U(n)max}$, %.

n	$K_{U(n)maxA}$	$K_{U(n)maxB}$	$K_{U(n)maxB}$
3	2.5	**3.9**	2.0
5	**12.7**	**12.3**	**12.3**
7	**12.8**	**11.8**	**12.8**
9	1.9	2.8	**3.3**
11	**4.6**	**4.6**	**3.6**
13	2.1	**3.1**	2.8
17	**3.3**	2.7	**3.4**
23	**3.1**	2.8	**3.4**

Table 3. Measured $K_{I(n)max}$, %.

n	$K_{I(n)maxA}$	$K_{I(n)maxB}$	$K_{I(n)maxC}$
3	7.1	3.9	3.6
5	6.8	4.2	4.9
7	6.7	1.7	3.3
9	2.9	1.5	1.6
11	3.9	0.8	1.2
13	1.9	1.1	1.7
17	2.3	0.5	1.5
23	2.7	0.2	0.6

6 Prediction of the influence of non-sinusoidal and unbalance voltages on induction motors of the coal sorting plant

At the coal sorting plant, 58 induction motors with a capacity from 4 to 185 kW are in operation. As an example, 2 induction motors with the power of 45 and 110 kW are taken for calculation. Table 4 presents their technical characteristics [21].

Table 4. Technical characteristics of induction motors.

Parameter	Motor type	
	3K280Sc8	3K315S4
P_N, kW	45	110
U_N, V	220	220
η_N, %	92	91
s_N, p.u.	0.014	0.023
b, 1/°C	0.052	0.052
K_{IL}, p.u.	5.0	7.0
$R'_{ST\text{-}S}$, p.u.	0.047	0.023
$X'_{ST\text{-}S}$, p.u.	0.110	0.122
$R'_{RO\text{-}S}$, p.u.	0.017	0.019
$X'_{RO\text{-}S}$, p.u.	0.12	0.16
T_{SSL}, years	20	20

The table shows: P_N, U_N, η_N,, s_N – the rated power, the voltage, the efficiency, the slip; b – the coefficient characterizing the insulation of the induction motor; K_{IL} – the locked-rotor current ratio at rated voltage; $R'_{ST\text{-}S}$, $X'_{ST\text{-}S}$ – the resistance and the inductance of the stator winding; $R'_{RO\text{-}S}$, $X'_{RO\text{-}S}$ – the resistance and the inductance of the rotor winding; T_{SSL} – the standard service life of the motor.

The calculation of characteristics that assess the influence of non-sinusoidal and unbalanced voltages on the induction motor was carried out using the program "Predicting the influence of non-sinusoidal unbalanced voltages on an induction motor". The screenshot of Sheet 1 of the program, which shows the modules of the program, is shown in Fig. 2.

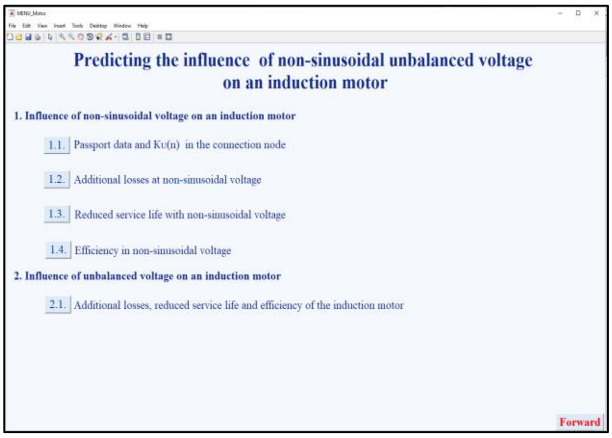

Fig. 2. Sheet 1 of the program.

Table 5 shows the characteristics that assess the influence of non-sinusoidal voltage on induction motors. The calculation results show that with the constant operation of the induction motor with a power of 45 kW at a non-sinusoidal voltage with the indices given in tables the actual service life can be reduced by almost 9 years. The service life of a 110 kW motor can be shortened by more than 3 years. The screenshot of the program showing the calculating the reduction in the service life of the induction motor with the power of 110 kW is shown in Fig. 3.

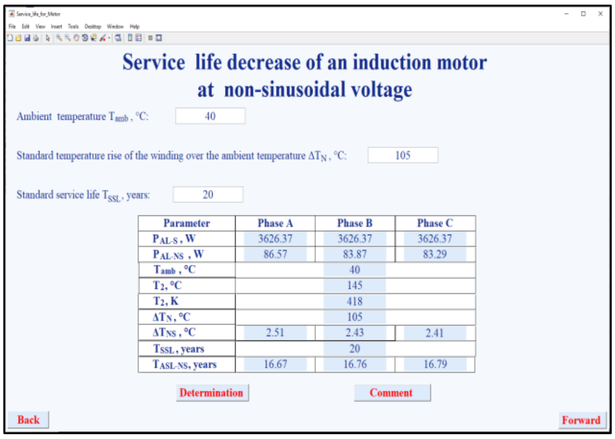

Fig. 3. Sheet of the program for calculating the service life decrease of the induction motor.

Table 5. Calculated characteristics at non-sinusoidal voltage.

Motor type		P_N, kW	$K_{U(n)}$, %	H_{NS}, %	$\Delta\eta$, %
3K280Sc8		45	Table 2	91.47	0.53
3K315S4		110	Table 2	90.81	0.19
Motor type		$P_{R\text{-}NS}$, W	$P_{OAL\text{-}NS}$, W	$P_{AL\text{-}NS}$, W	T_{ASL}, years
3K280Sc8	A	94.4	3.2	97.7	11.38
	B	91.7	3.1	94.8	11.56
	C	90.2	3.1	93.3	11.66
3K315S4	A	58.6	28.0	86.6	16.67
	B	56.9	27.0	83.9	16.76
	C	56.0	27.3	83.3	16.79

The screenshot of the program sheet, which presents the results of calculating the characteristics that assess the influence of unbalanced voltage on the induction motor with a power of 110 kW, is shown in Fig. 4.The calculated characteristics for two motors are given in Table 6. The calculation results show that since the voltage unbalance is negligible, the potential reduction in service life of induction motors is less than one year.

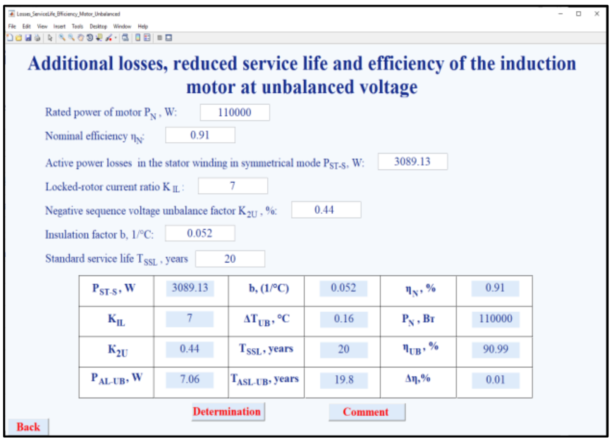

Fig. 4. Sheet of the program for calculating the characteristics of influence of unbalanced voltage on the induction motor.

Table 6. Calculated characteristics at unbalanced voltage.

Motor type	P_N, kW	K_{2U}, %	$P_{ST\text{-}S}$, W	$P_{\Sigma\text{-}UN}$, W
3K280Sc8	45	0.44	2673.15	3.12
3K315S4	110	0.44	3089.30	7.06
Motor type	ΔT_{UN}, °C	T_{ASL}, years	η_{UN}, %	$\Delta\eta$, %
3K280Sc8	0.16	19. 8	90.99	0.01
3K315S4	0.16	19.8	91.99	0.01

7 Conclusion

The calculation results show that non-sinusoidal and unbalanced voltages reduce the service life of induction motors. Their premature failure will lead to economic damage. Currently, the process of formation of intelligent electrical power systems is underway. Systems for continuous monitoring of indices of the power quality and parameters of the mode of electrical networks are being developed. They could be supplemented with programs for calculating characteristics that predict the influence of non-sinusoidal and unbalance modes on various electrical equipment, which would facilitate a prompt response to negative changes in the parameters in order to provide reliable, high quality, cost-effective power supply to consumers.

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