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Identifying the efficiency decrease factor of motors working under power harmornic in 660V electric mining grids

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Abstract

Purpose. Identify the motors efficiency decrease factor corresponding to various values of load-carrying ratio.

Methods. Basing on the onsite measurements of power harmonic in 660V low voltage (LV) grids in Vietnam underground mines, simulations have been done on MATLAB and compared with mathematical models. Verifying data will be implemented in Lab-measurements carried out on pumping system to reveal series of decreasing factors.

Findings. Series factors present the relation of the level of power total harmonic distortion (THD) and the decrease in motor efficiency with alternative load-carrying ratio. The factors will help mine operators to have better understanding of the power harmonics impact on 660V motors.

Originality. The proposed factors and simulation in MATLAB may be applied to all underground mining grids with different input parameters of THD.

Practical implications. The research is implemented to identify the factors obtained from the operation of motors which work in high power harmonic environment. The resulting factors could be utilized to recalculate mining efficiency.

Keywords: *mine, electric grids, harmonic, voltage, simulation*

1. Introduction

In the past 7 years, modernization has contributed greatly to the 25% increase in coal productivity of Vietnam underground mines [1]. The annual productivity growth is approximately 10%; going along with this increase, the numbers of power electronic devices utilized in mining have also seen a 47% rise (according to the data collected from 2015 to 2020).

Besides the increase in the nominal voltage of all underground mines from 380V to 660V, many kinds of power electronic equipment (including low voltage-660V and medium voltage-6kV units) are widely applied in the processing system, mining system as well as pumping and ventilating systems. Apart from technical enhancement, these apparatuses brought about a lot of issues to handle such as current and voltage distortion or grids' economical efficiency. Most of power electronic devices installed in underground mines contain passive filter to limit their harmful effect on power quality. However, the on-site measurements shown below testify to the negative result when power electronics inject a huge amount of power harmonics into the grid. Consequently, it leads to power loss, deterioration of voltage quality and distortion of other grid quantities.

Implementing the on-site measurement in 660V grid of Vietnam coal mine companies, we have deisgned resultant voltage and current wave forms that are shown in Figure 1. These Figures demonstrate that:

– the application of converters and inverters in 660V grid does not produce an impact on the magnitude of phase voltage, in most cases phase voltage is around 400V (Fig. 1a);

– even containing passive filter, the power electronic units in 660V underground coal mine still inject harmonics into the grid; at some moments the THD goes over the limit (Fig. 1b, THD of current harmonic is nearly 11.5%);

– because most of transformers contain delta coil, the triple harmonic order in the grid is eliminated. Therefore, popular orders of harmonics in 660V gird are 5th, 7th and 11th (as can be seen in Fig. 1c and 1d);

– in PCC (Point of Common Coupling) node, the THD is generally under the allowance limit [2], but in some branches of skeleton network, THD is over 5% (as can be seen in Fig. 1b);

– according to the accounting number of VINACOMIN [1], the number of harmonic generating devices in 660V grid increased about 15% a year, 88% of loads being ASMs (asynchronous motors). The motors often have loading ratio from 0.6 to 0.9 all the time.

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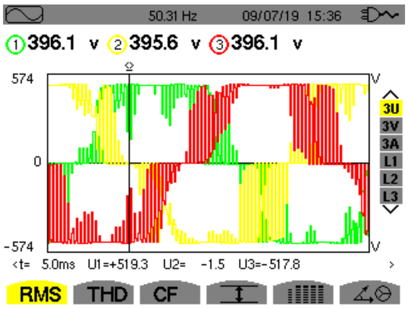
(a)



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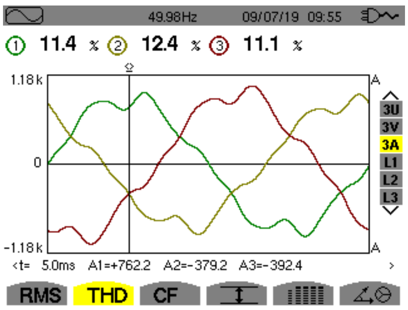

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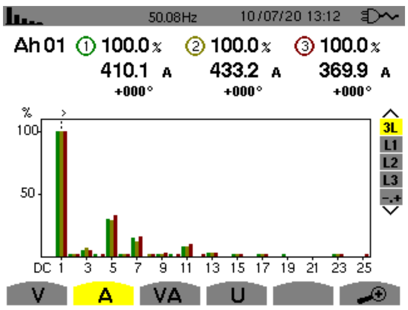

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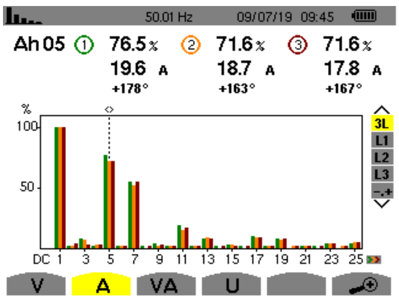

***Figure 1.** Harmonic analysis based on the on-site measurements in 2019 and 2020: (a) voltage waveform on-site measurement in DuongHuy company (measured on 09/July/2019; (b) current waveform distortion on-site measurement in DuongHuy company (measured on 09/July/2019); (c) THD analysis on-site measurement in KheCham company (measured on 10/July/2020); (d) THD analysis on-site measurement in HaLam company (measured on 09/July/2019)*

The above-mentioned violation will not have a short-time impact on equipment, conductors and grid. However, in the following part of paper, analysis will be implemented to identify the impact of harmonics on the decrease in ASM efficiency.

2. Theoretical basis

To analyze the impact of power harmonics on the electric grid, we must rely on understanding of power harmonic influence on motors and their internal conductors (motor winding). The most evident impact of harmonics is related to increasing heat inside the motors. This part presents the theoretical basis in the form of equations describing the change of losses in motors and their conductors considering power harmonics.

Depending on the magnitude of harmonics, the derating and losses increase of a motor are mainly caused by the increase in temperature inside the motor [2]-[6]. Particularly, winding loss in induction motors is related to series resistances, and it is proportional to the square of voltage. Winding loss is the sum of winding losses of harmonics and is calculated by Equation 1 [5], [7]-[9].

$$P_{cu-h} = \left(R_s + R_{rh}\right) \cdot I_h^2, \qquad (1)$$

where:

R_{rh} – rotor resistance for a harmonic in stator side view;

I_h – harmonic current calculated by the Equation 2:

$$I_h = \frac{V_h}{\left(\left(R_s + R_{rh}\right)^2 + \left(X_s + X_{rh}\right)^2\right)^{1/2}}. \qquad (2)$$

Thermal reaction of the motor operating under the impact of harmonics is investigated by the model presented in Figure 2 [7], [10]. The Figure is used to determine the increasing portion of power loss of the motor due to harmonics which results in the heat gain inside the motor.

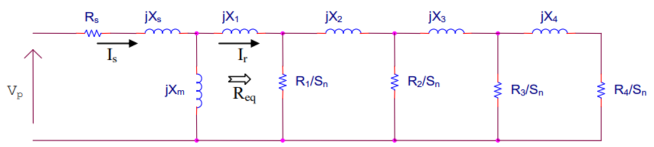

***Figure 2.** Model presenting the power loss of the motor under the impact of harmonics*

Figure 2 presents the skin effect impedance model for the equivalent circuit of induction motors; it can be simplified by Figure 3. In Figure 2, R_s, X_s are parameters characterizing the resistance and reactance of the rotor; X_m is the magnetizing reactance; I_s and I_r are respectively the currents of stator and rotor; S_n is the slip factor of the motor which depends on the order of the harmonic [10].

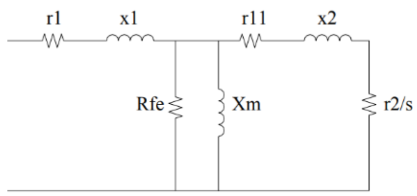

***Figure 3.** Single line diagram of induction motor considering harmonic*

Much research has been done to show the relation between motor power derating and the THD (total harmonic distortion) increase [9], [11], [12]. Generally, motor derating level is expressed by Equation 3:

$$D_h = 1 - \frac{P_{outh}}{P_{out}}, \tag{3}$$

where:

P_{outh} – output power of the motor when the source is nonsinusoidal, this power could be computed by applying the simple single diagram in Figure 3 [7];

P_{out} – output power of the motor when the source is sinusoidal.

In Equation (3) P_{outh} is also influenced by the slip factor that varies with harmonics according to Equation 4:

$$S_h = \frac{h+1-s}{h}, \tag{4}$$

where:

h – the order of harmonic;

s – the slip factor corresponding to fundamental frequency.

When a nonsinousoidal voltage is transmitted along a conductor (which is inserted on the periphery of rotor), the impact of harmonics on the conductor is mostly expressed by the skin effect and can be summarized as Figure 4 [13].

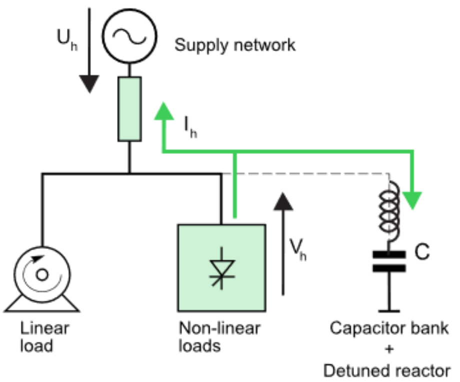

Figure 4. Single line diagram presenting the impact of nonsinusoidal source on conductors

As mentioned in [13], [14], "the resistance may increase due to skin effect and proximity effect. The former is a case where unequal flux linkages across the cross section of the conductor cause the AC current to flow on the outer periphery of the conductor. On the other hand, conductors that are spaced close to one another and carrying alternating current will have the current distribution in each conductor changed by mutual reactance".

Mathematically, many researches show an empirical equation (Eq. 5) that expresses the relation of power loss (pu) in cable and harmonics.

$$P_L = \left(a_1 x^2 + a_2 x + 1\right), \tag{5}$$

where:

a_1 and a_2 – constants depending upon: harmonic spectrum, type and cross section of the conductor.

The harmonic effect or THD values will also increase the Joules losses and current running on the conductor skin, the impact level shown in Figure 5. From the research into the losses in a conductor conside-ring the current magnitude, it is clear that the current magnitude and losses in the conductor are strongly related. When THD is lower than 10%, the losses caused by current (including harmonic currents) could be ignored.

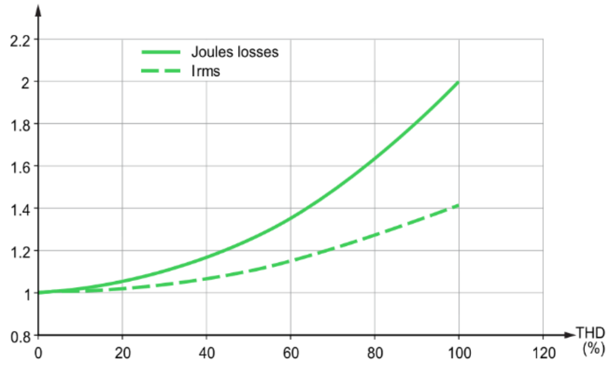

Figure 5. Curves presenting the impact of harmonic on current and Joules losses in the conductors' skin

When THD is bigger than 10%, there is a significant rise of losses when the current increases. Even when THD is 100%, the loss is doubled despite the fact that current has only 40% risen. Therefore, one must be very careful when making simulations to determine the losses of the motor with big value of THD. In the present research, all the Lab tests and simulations are carried out with THD lower than 5.5%.

3. Research results and discussion

3.1. Simulation models

Mining grid with 660V U_{nom} has been simulated in MATLAB. The Figure demonstrates that each motor has been set-up with individual parameters containing the varying load exerted by mechanical power on the motor shaft. At each section, a multifunctional measurement bar is configured to collect data including voltage, current, THD as well as power consumption of the motor. As mentioned in [15], to better understand the decrease in motor efficiency, the input mechanical load of the motor is varied, as shown in the detailed simulation model (Figs. 6 and 7). By changing the T_m (cyan blocks on Figure 8), the data expressing the impact of harmonics on the motor efficiency will be covered.

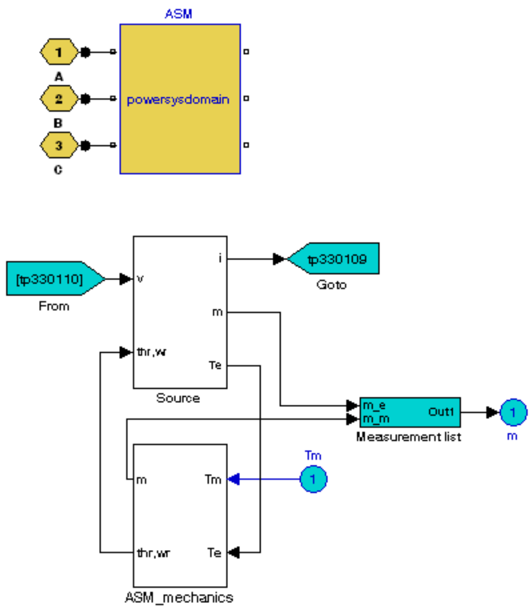

Figure 6. Model of multifunctional measurement bar located at each PCC of the grid

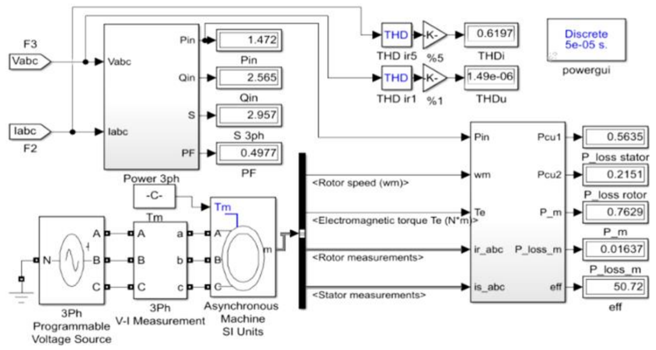

Figure 7. Model of a measurement block used to identify power consumption of each motor

3.2. Lab test, simulation results and discussion

Using diagrams in Figures 2, 3; Equation 1, 2 and 3 to simulate in MATLAB, we were able to design the resultant curve for the heat gain in the motor (with 70% nominal load) caused by harmonics (Fig. 9). This curve is used to compare the data with the Lab measurements, while the experimental parameters of motors shown in Figure 10 are listed in Table 1. The resultant heat is shown in Table 2.

Motor heat increase can lead to the increase in power loss in both rotor winding and stator winding [5], [6], [12], [14], [16]. Consequently, their efficiency is decreased. By simulating the operation of the above-mentioned motor (Table 1), we designed the curves presenting this decrease (Fig. 11).

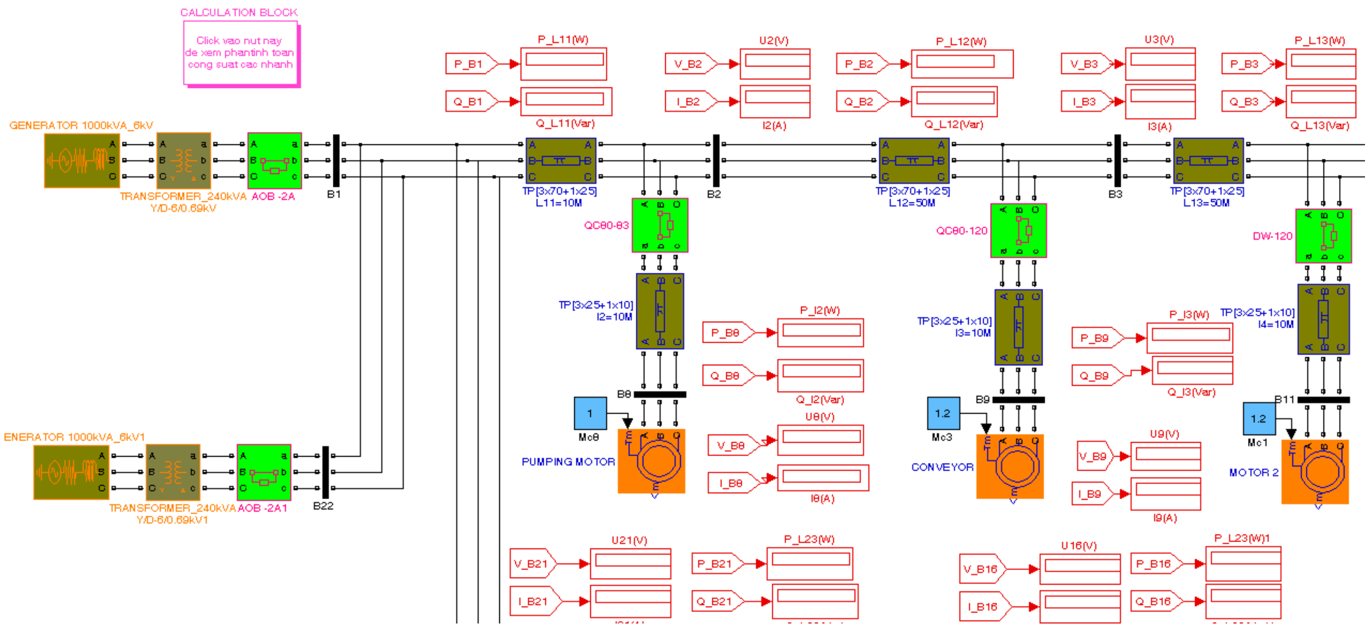

Figure 8. Simulation diagram of 660V grid in an underground mine

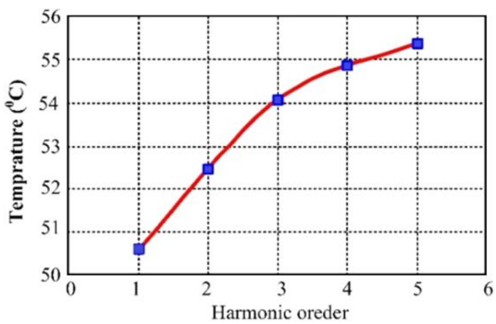

Figure 9. Curve showing the heat increase in motor operating under nonsinousoidal supply voltage

Table 1. Parameters of the motor during the Lab test

Parameter	U_{nom} (V)	Rotating speed (rpm)	No. of pole pair	P_{nom} (kW)	I_{nom} (A)
Value	380/660	1400	4	11	21

Table 2. Lab test results of temperature increase in the motor due to harmonic impact

Loading factor	50%	70%	80%	90%
Sinousoidal voltage source	46.1	50.3	52.3	53.5
Non-sinousoidal voltage source with 2nd order harmonic	49.2	52.8	55.8	57.1
Non-sinousoidal voltage source with 5th order harmonic	50.1	55.5	56.5	56.9

(a) (b)

Figure 10. Mine pumping system with inverters in the Lab: (a) measurement block at incoming feeder, distribution box containing 2 inverters used for 2 pumps; (b) installation of 2 pumps with power meters to measure power consumption

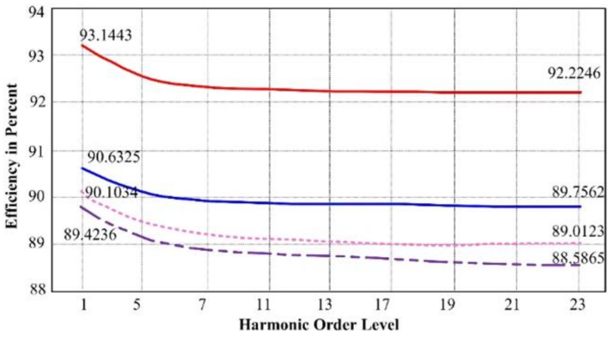

Figure 11. Motor efficiency decrease versus harmonic order (red, blue, pink and violet curves correspond to 90, 80, 70, 50% of loading factor respectively)

It is seen in Figure 11 that there is a sharp decrease in motor efficiency when the harmonic orders are in the range from 2nd to 4th. However, as shown in Figure 1, there are only 3 harmonic orders in 660V grid of underground mining: 5th, 7th, and 11th. Considering these harmonics individually, we can state that there is almost no difference in their effect on the motor efficiency reduction. For instance, with 70% loading, the three above mentioned harmonic orders cause the efficiency around 89 to 91%. It is again proved in the next part of the paper.

From the simulation and curves in Figure 9 it is obvious that when the motor operates under the impact of harmonics, its efficiency decreases from 12 to 7%. To verify this simulation, the Lab test was repeated several times with 2 motors (Table 1), the results obtained therefrom are shown in Table 3.

Table 3. Lab tests of motor efficiency with the impact of harmonics (%)

Harmonic order level \ Loading factor	50%	60%	70%	80%	90%
5th	88.8	89.8	90.2	90.4	92.6
7th	87.9	88.2	89.6	89.9	92.3
11th	87.5	88.3	89	89.9	92.1

In Table 3, the test is implemented with only 3 harmonic orders (5th, 7th, 11th). The results show that the average decrease in motor efficiency is around 9% (depending the loading factor).

Other calculations and simulations were carried out in a similar way for different typical motor power (in Vietnam underground mines) and THD, the results shown in Table 4.

Table 4. Motor efficiency (η) decrease with harmonic impact consideration (%)

THD (%) \ P_{nom} (kW)	18.5	37	75	114	Average value
5.5	9.23	9.68	9.38	9.57	9.465
5	8.18	8.56	8.23	8.45	8.355
4.5	7.65	7.45	7.38	7.48	7.490
4	7.14	7.22	7.18	7.26	7.200
3.5	6.39	6.45	6.381	6.53	6.438
3	6.02	5.93	6.09	6.084	6.031
2.5	5.53	5.483	5.519	5.601	5.533
2	5.47	5.44	5.463	5.389	5.44
1.5	2.211	2.672	2.322	2.385	2.398
1	1.87	1.921	1.932	1.894	1.904
0.5	1.011	1.121	1.132	1.114	1.095

As seen in Table 4, the test was conducted for 4 typical kinds of motors used in 660V electric system of underground mines. Although the THD of the grid is around the allowance limit of IEEE [2] the impact of harmonics on the motor power reduction is significant. Normally, the efficiency of motors drops by 5%, which means that 5% of the consumed power delivered from the source is emitted as unusable heat. It not only heats the motor but also decreases mining productivity. Therefore, the impact of harmonics on the increase in power loss could not be ignored even if harmonic pollution is within the range of limit.

4. Conclusions

By simulating the heat effect of the motor operating under harmonic impact, we analyzed and calculated the decrease in the motor efficiency factor for different loading factors. Based on the simulation and the Lab tests (which are compared), a cross-checking table is formed that will help an operator to identify the increase in power loss in motors when a harmonic source is injected into the grid.

Although the THD of the grid is limited by the allowance level [1], [2], [7] it results in nearly 10% power loss in motors. Respectively, this harmful influence could lead to significant motor derating.

The derating impact and increasing loss caused by harmonics are quite the same with motors despite their nominal power. These values mainly depend on the THD of the grid, therefore there should be passive filters installed in PCC nodes of the grid to lower the THD to 2%. Then the negative effect of harmonic pollution on motors could be ignored.

Acknowledgements

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References

[1] VINAMCOMIN. (2019). *Orientation for sustainable development of coal mining*. Approved by Priminister Dicision No 403/2016/QĐ-TTg. Available at: http://www.vinacomin.vn/dinh-huong-phat-trien-ben-vung-nganh-than-viet-nam-gan-voi-dam-bao-an-ninh-nang-luong/dinh-huong-phat-trien-ben-vung-nganh-than-viet-nam-gan-voi-dam-bao-an-ninh-nang-luong-201901181507032041.htm

[2] IEEE 519-1992. (1992). *Recommended practice and requirements for harmonics control in electrical power system.* Available at: https://ieeexplore.ieee.org/document/6826459

[3] Arslan, E., Sakar, S., & Balci, M.E. (2014). On the no-load loss of power transformers under voltages with sub-harmonics. *2014 IEEE International Energy Conference* (ENERGYCON). https://doi.org/10.1109/energycon.2014.6850433

[4] Ching-Yin Lee, Wei-Jen Lee, Yen-Nien Wang, & Jyh-Cherng Gu. (1998). Effects of voltage harmonics on the electrical and mechanical performance of a three-phase induction motor. *1998 IEEE Industrial and Commercial Power Systems Technical Conference*. Conference Record. Papers Presented at the 1998 Annual Meeting (Cat. No. 98CH36202). https://doi.org/10.1109/icps.1998.692550

[5] Adrian, S., Paul, P., Cristinel, H., & Mariana, M. (2012). Methodologies of measuring mechanical power delivered at the shaft of an induction motor driven by VFD. *INCAS Bulletin*, *4*(4), 161-170. https://doi.org/10.13111/2066-8201.2012.4.4.15

[6] Quispe, E.C., López, I.D., Ferreira, F.J.T.E., & Sousa, V. (2018). Unbalanced voltages impacts on the energy performance of induction motors. *International Journal of Electrical and Computer Engineering (IJECE)*, *8*(3), 1412-1422. https://doi.org/10.11591/ijece.v8i3.pp1412-1422

[7] Mirazamani, H.O., & Choobari, A.L. (n.d.). Study on performance of induction motors. *Paper research of Sharif University*.

[8] Elena, H., Ionel, L., & Anca, C. (2013). Impact of three-phase voltage dips on the induction motors – An experimental study. *4th International Symposium on Electrical and Electronics Engineering*. https://doi.org/10.1109/iseee.2013.6674352

[9] Mehrdad, M., Stanek, E.K., & Jannati, A.S. (n.d.). *Influence of voltage and current harmonics on behavior of electric devices*, 1-15.

[10] Oladokun, E. Faduyile. (2009). *Effect of harmonics on the efficiency of a three phase energy efficient and standard motors*. PhD Thesis. Chattanooga, United States: University of Tennessee.

[11] Rengifo, J., Salazar, H., Bueno, A., & Aller, J. (2017). Experimental evaluation of the voltage unbalance in the efficiency of induction motors. *IEEE Workshop on Power Electronics and Power Quality Applications*, (3), 1-6. https://doi.org/10.1109/PEPQA.2017.7981667

[12] Janak, P., & Kaur, R. (2014). Effect of harmonics on the performance characteristics of three phase squirrel cage induction motor. *International Journal of Review in Electronics & Communication Engineering*, *2*(2), 77-81.

[13] Gandhare, W.Z., & Patil, K.D. (2013). *Effects of harmonics on power loss in XPLE cables*. *Energy and Power Engineering*, *5*(4B), 1235-1239. https://doi.org/10.4236/epe.2013.54B234

[14] Giceva, I.Z., Sarac, V.J., Gelev, S.A., & Cingoski, V.T. (2018). Single phasing of three phase induction motors under various load conditions. *23rd International Scientific-Professional Conference on Information Technology (IT)*. https://doi.org/10.1109/spit.2018.8350459

[15] Do, N.Y., & Ngo, X.C. (2021). Influence of single phase voltage loss and Load carrying mode on mine drain pump motor in Vietmam. *Journal of the Polish Mineral Engineering Society*, *1*(20), 341-352. https://doi.org/10.29227/IM-2021-02-31

[16] Gouws, R. (2011). *Harmonic filtering and the effect of harmonics on induction motor efficiency*. Technical Report. Southern Africa: North-West University.

[17] IEEE C57.110-2018. (2018). *IEEE recommended practice for establishing liquid immersed and dry-type power and distribution transformer capability when supplying nonsinusoidal load currents*. https://doi.org/10.1109/IEEESTD.2018.8511103

Визначення фактору зниження ефективності двигунів, що працюють на гармоніці потужністю 660 В в електричних мережах шахти

Л.С. Тхань, Х.В. Бун

Мета. Визначення факторів зниження ефективності двигунів обладнання, що відповідає різним значенням коефіцієнта несучого навантаження в умовах вугільних шахт В'єтнаму.

Методика. Базуючись на вимірах місцевих гармонік потужності в мережах низької напруги (НН) 660 В у підземних шахтах В'єтнаму було проведено моделювання в MATLAB і порівняно з математичними моделями. Перевірка даних реалізована в лабораторних умовах, проведених на насосній системі, для виявлення ряду спадаючих факторів.

Результати. За допомогою моделювання теплового ефекту двигуна, що працює під впливом гармонік, проаналізовано та розраховано зниження коефіцієнта корисної дії двигуна для різних коефіцієнтів навантаження. Встановлено, що послідовні фактори представляють співвідношення рівня загальних гармонійних викривлень (ЗГВ) потужності і зниження ефективності двигуна з альтернативним коефіцієнтом несучого навантаження. Ці фактори допоможуть операторам шахт краще зрозуміти вплив гармонік потужності на двигуни 660 В. Визначено вплив зниження номінальних характеристик та збільшення втрат, спричинених гармоніками, однакових для двигунів, незважаючи на їхню номінальну потужність. Ці значення в основному залежать від мережі ЗГВ, тому у вузлах мережі точки загального зв'язку (ТЗЗ) повинні бути встановлені пасивні фільтри, щоб знизити ЗГВ до 2%.

Наукова новизна. Розширено область застосування встановлених факторів ефективності двигунів та підходів моделювання в MATLAB на всі мережі підземного видобутку з різними вхідними параметрами ЗГВ.

Практична значимість. Дослідження реалізовано з метою виявлення факторів, отриманих від роботи двигунів, які працюють у високопотужному гармонійному середовищі. Отримані фактори можуть бути використані для перерахунку ефективності видобутку.

Ключові слова: *шахта, електромережа, гармоніка, напруга, моделювання*

Определение фактора снижения эффективности двигателей, работающих на гармонике мощностью 660 В в электрических сетях шахты

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Цель. Определение факторов снижения эффективности двигателей оборудования, что соответствует разным значениям коэффициента несущей нагрузки в условиях угольных шахт Вьетнама.

Методика. Основываясь на измерениях местных гармоник мощности в сетях низкого напряжения (НН) 660 В в подземных шахтах Вьетнама, было проведено моделирование в MATLAB и в сравнении с математическими моделями. Проверка данных реализована в лабораторных условиях, проводимых на насосной системе, для обнаружения ряда убывающих факторов.

Результаты. С помощью моделирования теплового эффекта двигателя, работающего под влиянием гармоник, проанализировано и рассчитано снижение коэффициента полезного действия двигателя для различных коэффициентов нагрузки. Установлено, что последовательные факторы представляют соотношение уровня общих гармонических искажений (ОГИ) мощности и снижение эффективности двигателя с альтернативным коэффициентом несущей нагрузки. Эти факторы помогут операторам шахт лучше понять влияние гармоник мощности на двигателе 660 В. Определено влияние снижения номинальных характеристик и увеличения потерь, вызванных гармониками, одинаковых для двигателей, несмотря на их номинальную мощность. Эти значения в основном зависят от сети ОГИ, поэтому в узлах сети точки общей связи (ТОС) должны быть установлены пассивные фильтры, чтобы снизить ОГИ до 2%.

Научная новизна. Расширена область применения установленных факторов эффективности двигателей и подходов моделирования в MATLAB на все сети подземной добычи с разными входными параметрами ОГИ.

Практическая значимость. Исследование реализовано с целью выявления факторов, полученных от работы двигателей, работающих в высокомощной гармонической среде. Полученные факторы могут использоваться для пересчета эффективности добычи.

Ключевые слова: *шахта, электросеть, гармоника, напряжение, моделирование*