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The Evaluation of Medium Voltage Motor's Current and Voltage Harmonics During the Loading Conditions

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Summary: **This paper presents the results of investigating harmonic levels on medium voltage motors at loading conditions in air separation plants. The essential results of the measurement of the medium voltage motor harmonics are summarized in the values for the total harmonic distortion (THD). Motors loading case is used to assess the current and voltage harmonic distortions. Proper system analysis is important when adding any new motor starting and controlling equipment. It will be able to better suggest the most appropriate starting and control method. Two medium voltage motors of air separation unit' measurement results and simulations are summarized. Both current and voltage harmonic distortions are fitted linear regression model. The predicting THD values can be used for this kind of process for future planning.**

Key words:
motor loading, harmonics, regression analysis

1. INTRODUCTION

Motors have the undesirable effect of drawing several times their full load current while motor starting. This large current flowing trough the system impedances will cause voltage sag that may dim lights, cause contactors to drop out, and disrupt sensitive equipment. The situation is made worse by an extremely poor starting displacement factor. The time required for the motor to accelerate to rated speed increases with the magnitude of the sag, and excessive sag may prevent the motor from starting successfully [1].

There are several researches on motor starting and control methods for medium voltage motors [2-3]. They will summarize common methods and provide application guidelines for proper selection considering the distribution system, driven equipment, speed-torque issues, starter method limitations and economics [3]. Interactions of reaccelerating motors dynamic simulations were chosen. The results of dynamic analysis are belonging to a plant where about 350 motors are assigned to automatic reaccelerating. The system involves massive restarting of motors on a power system that is already weakened by at least one contingency and without the benefit of offloading motors. Therefore, all motors are restarted under full load condition [4].

Several authors also interested voltage sag caused by motor energization. It has been seen how the deceleration and acceleration of motors influences duration and shape of voltage sags [5]. Taking motor behaviors into account will make it no longer possible to define sag simply by its duration and magnitude. The influence of motors on the shape of voltage sags is discussed in detail [5-6]. This paper presents the applications of regression models to predict the future growth trend of THD of 40 power transformers from field measurement data. The prediction values are important and can be used for transformer planning [7].

All authors mention the influence of voltage sag on motor behaviors or voltage sags due to motor starting, but not the influence of motors approximately no load current spectra to power quality. In this study, beside voltage sag that caused the medium voltage motor energized the effect when the motor loading takes a long time current and voltage harmonic distortion measured and examined. In chemical process all big air separation unit compressors are fed from medium voltage and these motors reach their nominal load approximately in 7-8 hours. If there are more than one motor supplied from a bus and no countermeasures are taken, existing harmonic distortions could reach dangerous limits.

2. SYSTEM DESCRIPTION

2.1. Process Description

Air separation plants produce nitrogen, oxygen and argon using air and electrical power as raw materials. The basic process for large-scale air separation process has remained unchanged for decades [8-9]. An air separation plant consists mainly of five steps as shown in Fig.1.

— Filtering and compressing air,
— Removing contaminants, including water vapor and carbon dioxide (which would freeze in the process),
— Cooling the air to very low temperature through heat exchange and refrigeration processes,

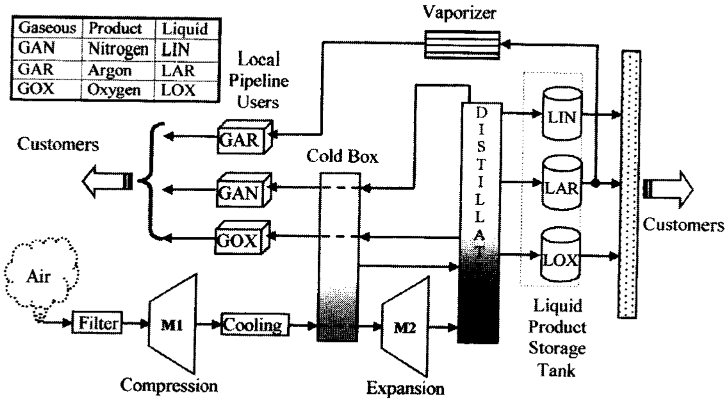


Fig. 1. Gas production flow outline

— Distilling the partially-condensed air (at about -300°F / -185°C) to produce desired products,

— Warming gaseous products and waste streams by heat exchange with incoming air

All air separation processes start with compression of air. Electric power is used to drive most of the compression equipment. Additional compression equipment may be used to raise product gas pressures to the required distribution pressure. More compressors are used to produce additional refrigeration to when products are produced as liquids. Purchase of electricity is the largest operating cost incurred in air separation plants. When the two motors are loaded to their nominal load, liquid and gas phase production starts. Plants daily liquid phase production capacity is approximately 140 Ton/day. It consists of 120 T/day LOX, 15 T/day LIN and 5 T/day LOX.

2. ELECTRICAL DESCRIPTION

Air separation plant installed power is 35MVA. Plant is feeding from 154/34.5 kV substation. There are three transformer ratings, one of them 30 MVA power transformer 34.5/6.3 kV, the others are 2500 kVA and 1000 kVA 34.5/0.4kV auxiliary supply transformers. There are two medium voltage motors which names are M1 and M2. 30 MVA power transformer supplies only M1 and M2 motor's electrical consumption. And also medium voltage motors are started direct online and unloaded. M1 and M2 motor's reactive power compensation is done locally. Compensation groups are connected star and withstand 7.2 kV.

After filtering the air is compressed by M1. The compressed air is then cooled to close-to-ambient temperature by passing through water-cooled or air-cooled heat exchangers. This cooling period is approximately 5 hours long and temperature about -185°C. During the cooling period M2 is switched off. The cooling is accomplished with cold product and waste gas streams exiting the separation process.

When proper conditions are met, M2 is switch on. After that M2 is loaded step by step and reaches nominal load about 3-4 hours. Distillation columns separate the air into desired products. Oxygen plants will have both high and low pressure columns where impure oxygen from the high-pressure column receives further purification in the low-pressure column. Nitrogen plants may have only one column, although many also have two. Because the boiling points for oxygen and argon are similar, plants producing very high purity oxygen require more distillation stages and remove argon from a near the mid-point of the low pressure column where its concentration is highest. The parameters of medium voltage motors are given in Table I.

M2 motors torque-speed-current is represented in Fig. 3. Along with the aforementioned basic information, this is required for a voltage drop type of motor starting analysis. Several other items are also required for the detailed speed-torque and accelerating analysis. These include speed-torque characteristic of both motor and load.

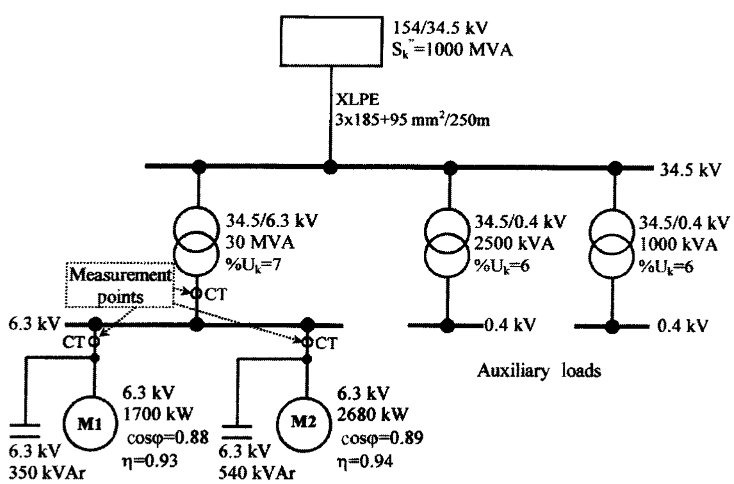


Fig.2. Single line diagram of electrical separation unit

3. SIMULATED AND MEASURED INDUSTRIAL SYSTEM VALUES

3.1. Site Survey

Fig. 2. shows a sketch of measurement at a secondary site. Three power analyzers are used to measure systems parameters. One of them is Fluke 199-C scopemeter and the others are Circutor AR5 network power analyzers. Motors inrush current's maximum magnitude and time are measured with soope meter 199-C (200MHz).

It is decided that for reasons of numerical accuracy, the sampling rate is samples 1250 samples/s or 24 samples for one 50 Hz period which more than adequately satisfies the Nyquists criterion. After motors are switched on to reach their nominal loading conditions, Circutor AR5 network analyzers measured current, voltage, total and individual harmonic distortions. Circutor AR5 takes samples in every 5 seconds. Periodic variations in current and voltage magnitudes and harmonic distortion levels can be studied more precisely.

M1 runs at 09:07 and electrical data are stored simultaneously. M1's inrush current peak is determined 950A. It is approximately 5,1 times of M1 nominal current. After M1's inrush conditions, no load current is measured as 66A. Cooling period is completed about 6 hours depending on air temperature and humidity. M1 motor's current is reached 102,5 A by 17:20. These values are shown at Fig. 4.

After correspond the appropriate system conditions, M2 motor is switch on manually. M2's inrush current peak is 1300A. It is approximately 4.7 times of M2 nominal current. After M2's inrush conditions, no load current is 74A. M2 motor is loaded step by step. It reaches operation condition about 4 hours. These values are showed at Fig. 5.

Motors starting currents can be seen in Fig. 4 and 5 sampled on 5 sec. In this way motor inrush currents pick and period value can no be determined exactly. For this reason these currents are also measured by Fluke 199C energy analyzer at the same time. Measured values are given in Fig. 6a and 6b. M1 and M2 motor's inrush conditions are finished 5.7s and 6.4s under no load, respectively. Maximum starting currents and starting periods of both motors can be seen from the figures.

All current and voltage signals contain 30.000 samples. Staring of induction motors leads to voltage sags. Motor's terminal voltage rms value is determined for better understanding of voltage sag. The rms value is calculated every cycle. This is done by using the following equation:

$$V_{RMS}(kN) = \sqrt{\frac{1}{N} \sum_{i=(k-1)N+1}^{i=kN} v_i^2} \qquad (1)$$

Where N is the number of samples per cycle, v_i is the sample voltage in the time domain [10]. The algorithm described at equation 1 has been applied to the sag shown in Fig. 7. In Fig. 7 the rms voltage has been calculated over a window of one cycle, which 24 samples for the recording used.

Table 1. Induction motor parameters

MOTOR	M1	M2
R_s (ohm)	0,0423	0,0759
X_s (ohm)	1,4713	1,6094
X_m (ohm)	69,43	75,35
R_r (ohm)	0,0423	0,0526
X_r (ohm)	1,1323	1,1668
H (kgm^2)	45	50
S (kVA)	1828	2851
V (kV)	6,3	6,3

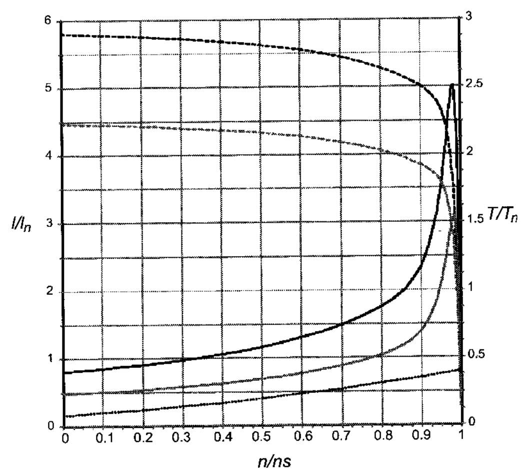


Fig. 3. M2 motor's speed-torque characteristics

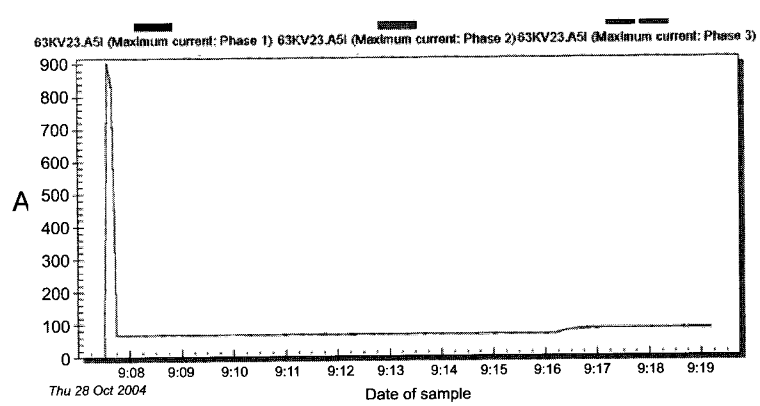


Fig. 4. M1 motor's current derivations

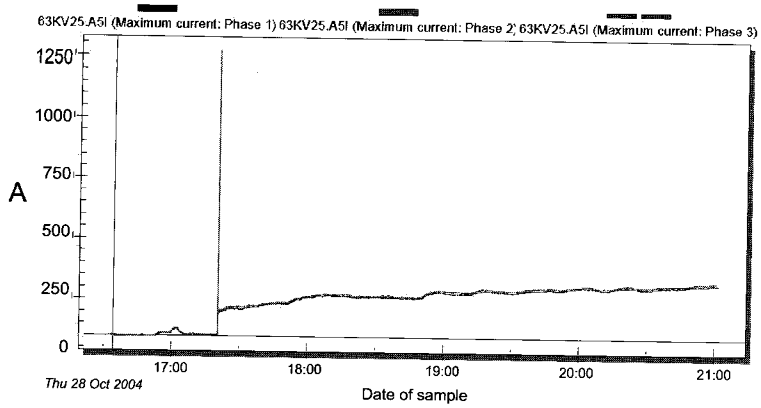
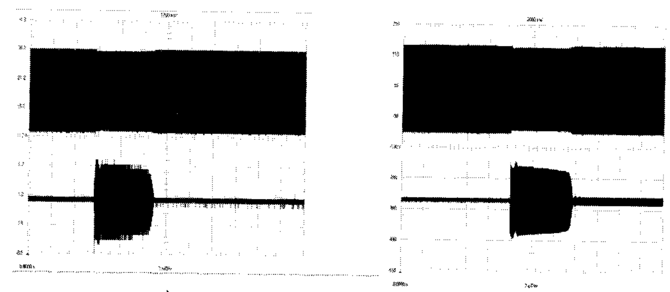
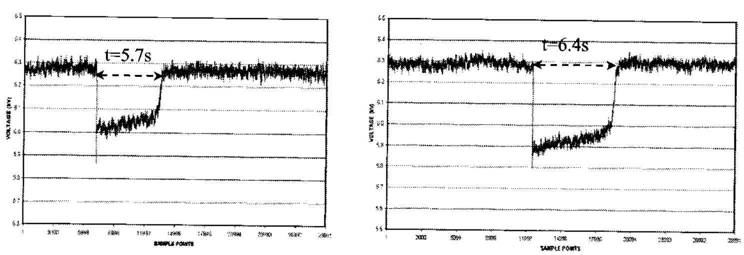


Fig. 5. M2 motor's current derivations



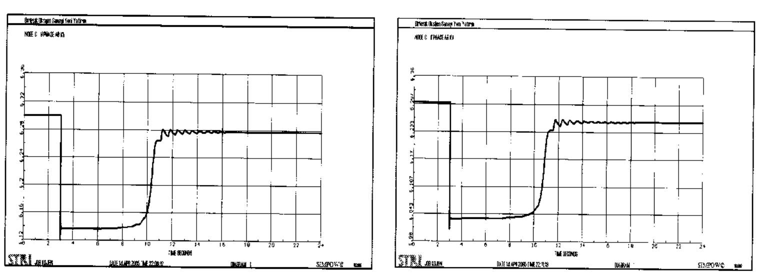
a) b)

Fig. 6. Current and voltage variations of motors at starting a) M1 b) M2



a) b)

Fig. 7. a) M1 motor sag in real system, b) M2 motor sag in real system



a) b)

Fig. 8. Motors' voltage sag in simulation a) M1, b) M2

3. 2. Simulation Study

The required calculation is fairly complicated and is left to a motor starting or general transient analysis computer program. Parameter values for standard induction motor equivalent circuit, including number of motor poles and rated rpm, inertia constant values for the motor and the motor load, torque versus speed characteristic for the motor load data will be required for the simulations.

Supply system and motor data is given in seatrown 2.2. Contrary to many analyzing programs, SIMPOW is examining motor parameters rotor resistance change dependent on slip [11]. Program has two modes as a masta and transta. Masta simulates instantaneous values of voltages and currents of the network and other primary components of the power system, while Transta simulates the power-frequency components only, expressed as phasors. In this study transta model is used.

For this reason slip values bound to the rotor resistance are calculated from motor characteristics given in Fig 3. Analyses done with obtained motor and load characteristics, system parameters and same results with the measurement values are obtained. Sag values at Fig. 7 exactly reached and simulation results are given in Fig. 8.

4. CURRENT AND VOLTAGE DEVIATION DURING THE MOTOR LOADING

The motor' loading currents versus time is shown in Fig.2 and 3. The loading currents versus THD_I and THD_V are represented in Fig. 9. It is obvious that THD_I and THD_V follow the variation of load current. In order to obtain the information after load increase, regression model analysis is adopted. It can predict the dependent variable, y_i, as a linear function with one independent variable, x_i. In order to predict THD_I and THD_V levels from motor loading current regression model is adopted. In this work, background harmonic voltage levels are neglected.

The task of estimation is to determine regression coefficients β_0 and β_1, estimates of the unknown parameters β_0 and β_1 respectively. The estimated equation will have the form:

$$\hat{y} = \beta_0 + \beta_1 x \qquad (2)$$

where x, load current; $\hat{y}$, estimate of THD_I (THD_V).

The basic technique for determining the coefficients β_0 and β_1 is Ordinary Least Squares (OLS), values for β_0 and β_1 are chosen so as to sum of the squared residuals (SSR).

$$\beta_0 = \bar{y} - \beta_1 \bar{x} \qquad (3)$$

$$\beta_1 = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2} \qquad (4)$$

where x_i, load current at the i^{th} observation; y_i, THD_V or THD_I at the i^{th} observation; x, mean value of load current; y, mean value of THD_V or THD_I.

In order to identify the goodness of fitting a regression model to the measurement data, the coefficient of determination R^2 is shown:

$$R^2 = \frac{\sum (\hat{y}_i - \bar{y})}{\sum (y_i - \bar{y})^2} \qquad (5)$$

R^2 value is between 0 and 1. The more R^2 value is close to 1, the more strong relationship is in predicting y.

In order to get harmonic information of a power system, field measurement is the best way for the utility. Motor feeding bus' harmonic voltage distortions are related with harmonic current distortions. Regression models can provide a good tool for predicting loading trend of harmonic distortions.

With measurement data in Fig.9, the regression models of THD_i versus load current for the M1 and M2 is represented in Fig 9a-9b, respectively.

M1 and M2 motor' regression models are shown in Equation 6 and 7. M2' R^2 values are better than M1'.

$$THD_I(\%) = -0.0041.I + 1.3353 \qquad R^2{=}0.7385 \quad \text{for M1} \qquad (6)$$

$$THD_I(\%) = -0.0061.I + 1.4846 \qquad R^2{=}0.9143 \quad \text{for M2} \qquad (7)$$

Fig. 10 shows addition of M1 and M2 loading current versus THD_I (%). M1 motor reaches nominal current at 112 A by 5 hours. Motor THD_I (%) decreases from %1,6 to % 0.7 throughout the loading. Motors THD_V (%) deviations as same with THD_I (%). It is represented in Fig. 11. When first motor reaches nominal current and to meet system conditions M2 motor approximately started at 120 A. Feeder current reaches from 120 A to 300 A approximately 3 hours.

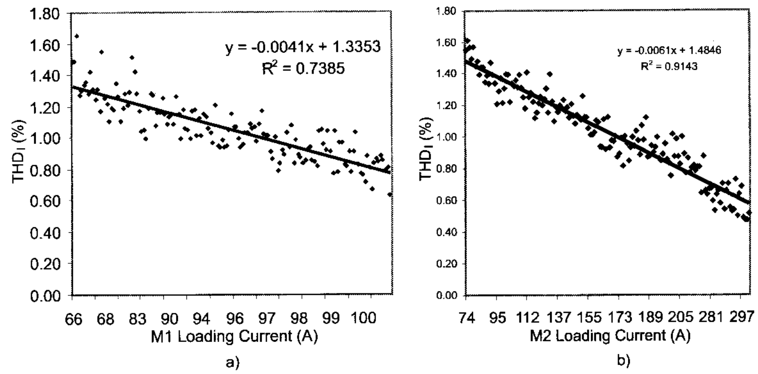


Fig. 9. The regression models of THD_I versus load current of a) M1 and b) M2

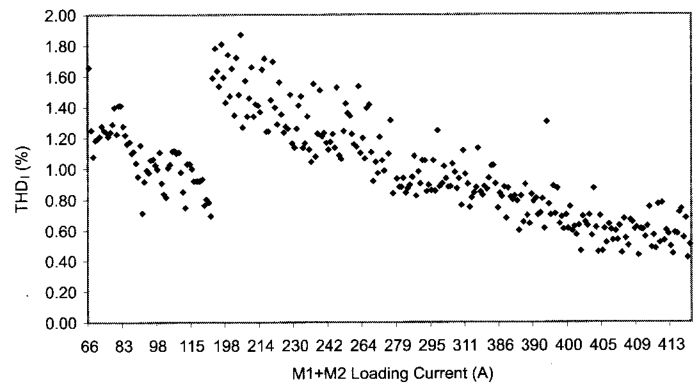


Fig. 10. THD_I (%) versus load current M1+M2

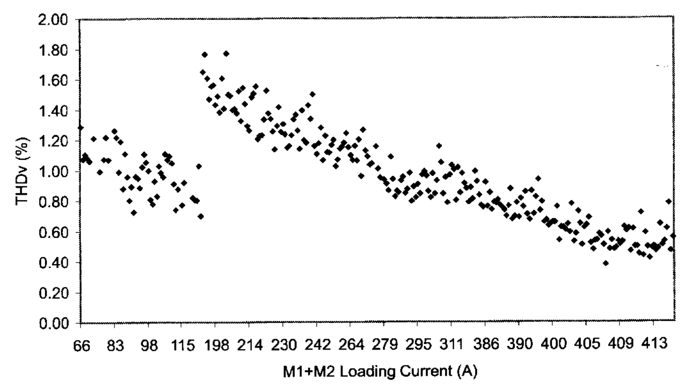


Fig. 11. THD_V (%) versus load current M1+M2

6. CONCLUSION

In many parts of the world, the actual voltage distortion levels are maintained within the planning level by imposing appropriate emission limits to the harmonic line current limits. To determine appropriate equipment emission limits, both measurement campaigns and simulations are required to study the harmonic propagation in an actual network. This paper presents the applications of regression models from measurement data predict for total harmonic distortions on coordination loading. The method is tested on an existing air separation plant by using simulation and field measurement. Results are very appreciated. The predicting values can be used by the utility for future planning.

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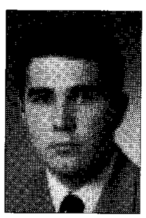

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