Journal of Computations & Modelling, vol.4, no.1, 2014, 39-51
ISSN: 1792-7625 (print), 1792-8850 (online)
Scienpress Ltd, 2014

Electric Machine Experimental Monitoring System based on Labview Environment

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Abstract.

It is widely accepted that contemporary scientific experimentation on electrical machines requires extensive measurements and acquisition of various data. The equipment used for this purpose is usually quite expensive and dedicated to a specific application. In this paper the development of a programmable, versatile and inexpensive system based on Labview environment is described. This is able to perform an essentially limitless number of simultaneous measurements on any kind of experimental or applied installation. Furthermore, the same system is able to perform extensive signal conditioning and processing, in order to automatically produce complex graphs and facilitate the drawing of conclusions. Finally, the same system may actively control electrical equipment allowing for even more complex experiments to be performed. In this case, an ac/ac converter supplies power to an electric motor. Six differential voltages and six currents are measured and recorded in real time, while power, total harmonic distortion etc are calculated, in order to determine whether the use of the ac/ac converter is efficient or not.

Keywords: Data acquisition, LabView, measurement system, induction motor, power electronics.

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1. Introduction

The basis of any scientific experimentation is the ability to perform measurements. The simplest phenomena on electrical machines are related to their steady-state behavior. These can easily be studied with the use of common instruments like V-meters, A-meters, oscilloscopes etc. However, when more complex phenomena need to be studied like transient behavior, notches and harmonic distortion, then more sophisticated equipment is required. Such instruments are multichannel oscilloscopes, measurement recorders etc, which are very expensive and many times prove to be inadequate.

The introduction of data acquisition devices solved all these problems by offering accurate and high-speed equipment that can use regular PCs to store and process very large amounts of measurements. Furthermore, they can provide interactive and smart collection of data, accelerating and facilitating the work of the researcher.

2 What is a DAQ?

Today, commercial Data AcQuisition devices (DAQs) allow for the simultaneous input of 16, 32 or more voltages at sampling speeds that range from a few kHz to many GHz. Conversion from analog to digital is not a problem, because the resolution provided can be quite high (24 bits or more). This data may be processed extensively in a computer to provide real-time results with no effort.

Moreover, DAQ devices may also output several voltages to drive analog actuators. This way, very complex experiments can be implemented. In addition to the above, numerous digital inputs and outputs are also provided, allowing for multiple triggers, switch activation etc.

Such multiple analog and digital input / output systems, with the processing power provided by computers, can be networked together to form a cluster of virtually infinite measuring potential.

There are several ways to program a DAQ device, using general purpose languages like C++ or specific graphic environments like LabVIEW. The latter allows for the creation of the so called “virtual instruments”, which can be fully customized. All dataflow from measurement and data processing to data storage, results presentation and signal output is programmed using graphic blocks, much like Matlab’s Simulink.

3 Developed DAQ System

3.1 The initial problem of energy efficiency study of topologies for power converters & electrical motors

Modern warships are equipped with many induction motors of different nominal powers ranging from a few hundred Watts up to several MW. Most of them are three-phase squirrel type induction motors, with the exception of small one-phase motors used in accommodation spaces and large multi-phase propulsion motors [1]. The performance of the induction motor is quite satisfying when it is operating close to its nominal power and speed [2].

However, its high starting current and low starting torque drastically reduce its efficiency, especially if the motor repeatedly starts and stops only to run for short time intervals. Electrical equipment manufacturers state that the use of power electronics is the solution to achieve energy saving [3]. This is true because power electronics significantly limit the starting current and its respective losses. They can also increase the motor’s efficiency by supplying it with variable voltage and frequency, in order to drive it on its optimum operating point for each load. This is calculated by a specialized automatic control system.

On the other hand, power electronics cause power quality problems, like harmonic injection. The existence of current and voltage harmonics in their output causes additional power loss on the induction motor, because of magnetic hysteresis losses, eddy currents on the core and of skin effect on copper windings. Also, the existence of current harmonics in their input causes additional power loss on the cables and bus-bars, because of skin effect and operational problems in other electrical equipment. Some of them are inaccurate operation of automatic control systems, flickering phenomenon at fluorescent lamps etc.

3.2 The prototype data acquisition system

In previous work [4], an experimental setup was implemented to verify and approximately quantify the efficiency of driving a motor with a power-electronics converter. In this setup, a three-phase squirrel induction motor is driving an electrodynamometer which represents the mechanical load (i.e. a pump, a fuel oil separator etc). This motor is powered by a regular three-phase power supply, either directly or through an AC/DC/AC electronic converter. The basic topology and a photo of the experimental setup are shown in Figures 1 and 2 respectively.

All six voltages are measured, in respect to the neutral, using differential voltage probes with a transformation ratio of 1:200 (see Fig. 3). Also, all six line currents are measured using current probes (clamps) with a transformation ratio of 1A:500 mV (see Fig. 4). In order to amplify the weak current signal, each line is turned over the clamp four times.

All these signals are collected and properly sampled by the heart of the system, which is a data acquisition USB device (see Fig.5), with 16 multiplexed analog inputs and a maximum combined sampling rate of 200 KS/s [5].

In this setup, 12 inputs are used and sampled at 13 kHz each. From these inputs, measurements are acquired, processed, displayed and stored in bunches of 500 samples per input.

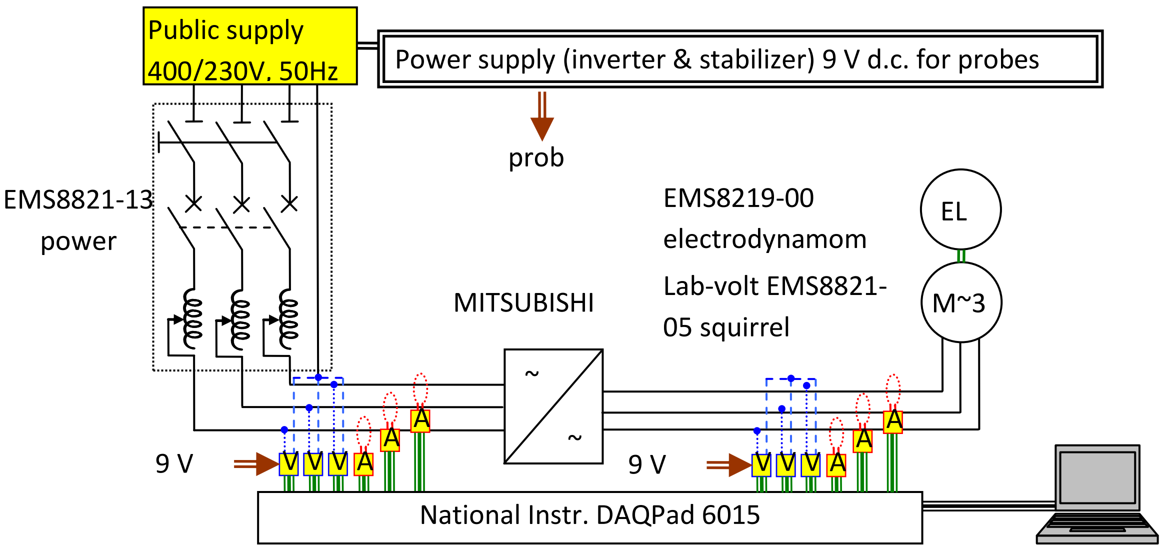

Figure 1. Detailed block diagram of the experimental setup
(the supply of the excitation winding of the electrodynamometer is omitted for simplicity).

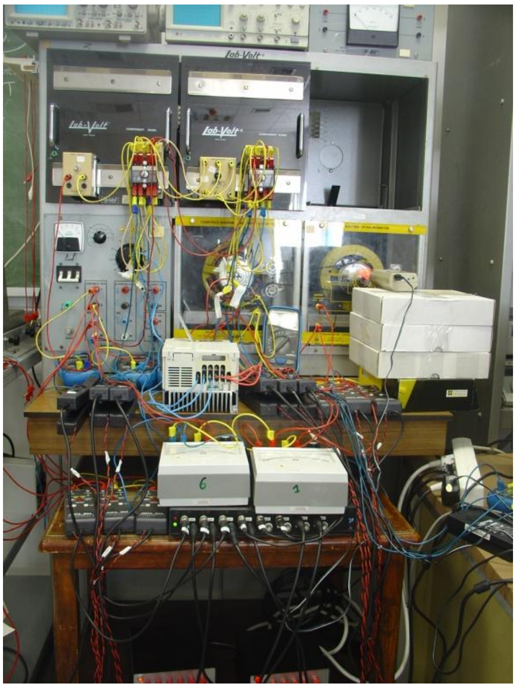

Figure 2. Photo of the experimental topology.

Figure 3. HAMEG Instruments HZ-100 differential voltage probe.

Figure 4. Chauvin Arnoux E3N current probe.

Figure 5. National Instruments DAQPad 6015 data acquisition device.

The inputs are multiplexed, meaning that they are not sampled simultaneously, which could lead to erroneous results. However, since the time required to receive a sample from every input is much smaller than the 0.02sec – that correspond to the 50Hz frequency of the mains – the measurements may be considered simultaneous.

All the above are adjusted and controlled by a PC connected to the DAQ device. This PC is programmed using a block-diagram style environment called LabVIEW (see Fig.6). With this one can create very versatile custom views of data representation and control called Virtual Instruments (see Fig.7).

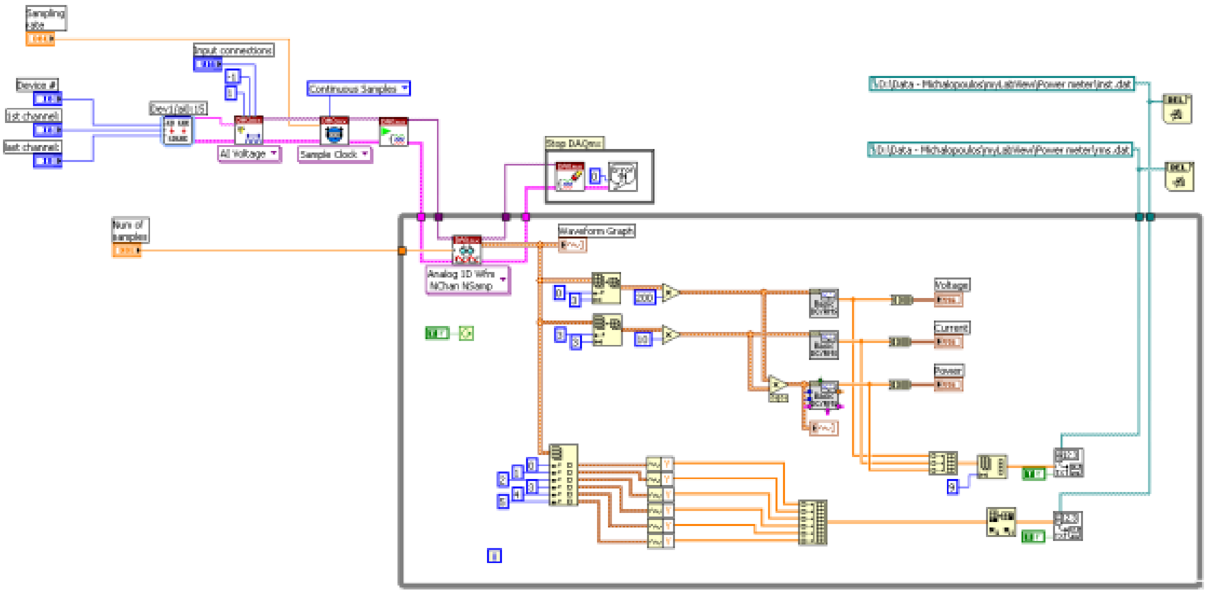

Figure 6.

LabVIEW algorithm.

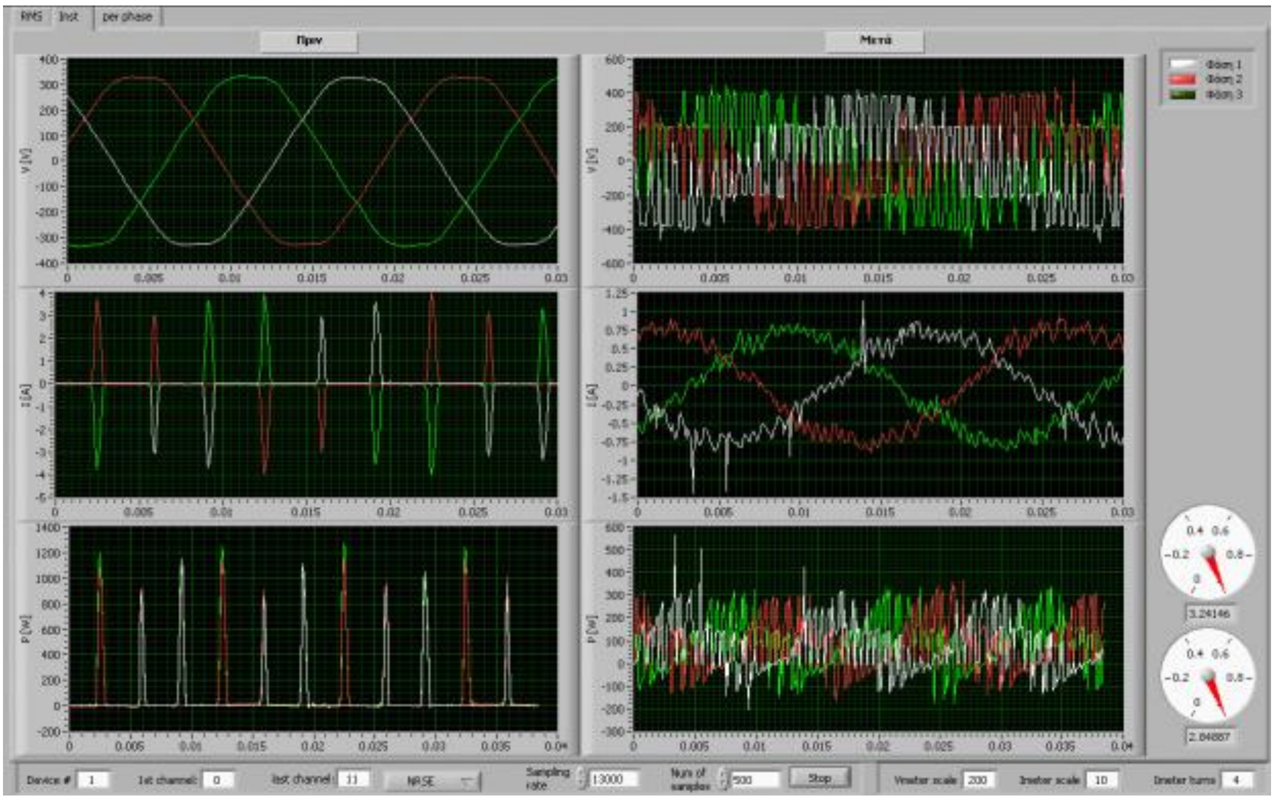

Figure 7.

Virtual Instrument showing instant voltages, currents and power per phase.

The algorithm created here performs the following:

- Virtual presentation and data storage of instant line-to-neutral voltages $v_i(t)$, of instant line currents $i_i(t)$ and of instant power $p_i(t)$ for the three phases i=a,b,c of the converter input and the converter output with respect to time t (see Fig. 6). Taking into consideration the transformation ratio of differential voltage probes A_V, the transformation ratio of current probes A_I and the number of turns at the clamps (*turns*), the instant power $p_i(t)$ is then calculated as:

$$p_i(t) = \left(A_V \cdot v_i(t)\right) \cdot \left(\frac{A_I \cdot i_i(t)}{turns}\right) \quad i=\text{a, b, c} \quad (1)$$

- Virtual presentation and data registration of root mean square (R.M.S.) line-to-neutral voltages $\tilde{V}_i$, R.M.S. of line currents $\tilde{I}_i$ and of active power P_{in-i} for the three phases i=a,b,c of the converter input and the converter output with respect to time (see Fig.8). The respective calculations for R.M.S. line-to-neutral voltages are realized as:

$$\tilde{V}_i = \sqrt{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} v_i^2(t) \cdot dt} \overset{\tau = \frac{T}{N_T} = \frac{k \cdot T}{k \cdot N_T} = \frac{t_2 - t_1}{k \cdot N_T}}{\Rightarrow} \tilde{V}_i = \sqrt{\frac{1}{T} \cdot \sum_{i=1}^{k \cdot N_T} v_i^2(i \cdot \tau) \cdot \frac{T}{k \cdot N_T}} \Rightarrow$$

$$\tilde{V}_i = \sqrt{\frac{1}{N_T} \cdot \sum_{i=1}^{N_T} v_i^2(i \cdot \tau)}$$

Where t_2-t_1=k·T, k is an integer number and T is the period of the three-phase supply voltage $V_a(t)$- $V_b(t)$- $V_c(t)$. Because of the multiplication factor A_V of the voltage probe, finally the respective values of R.M.S. voltages are equal to:

$$\tilde{V}_i = A_V \cdot \sqrt{\frac{1}{N_T} \cdot \sum_{i=1}^{N_T} v_i^2(i \cdot \tau)} \quad i=\text{a, b, c} \quad (2)$$

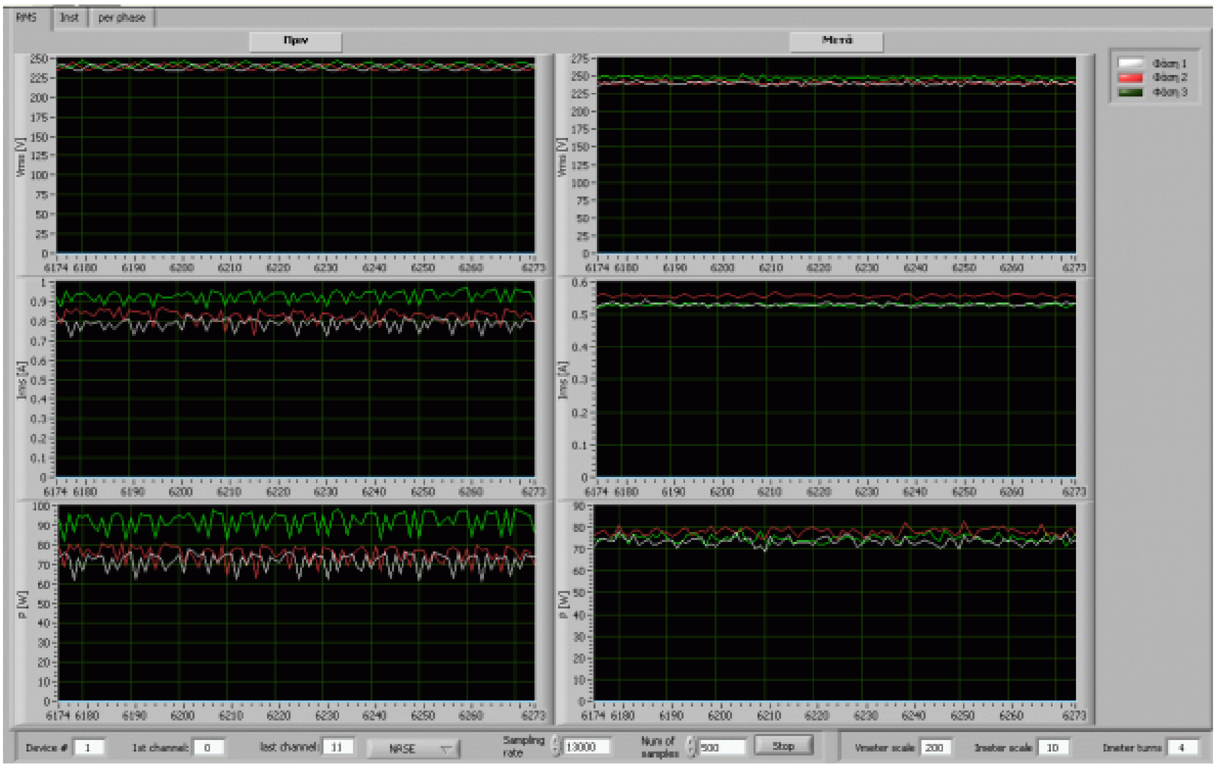

Figure 8. Virtual instrument showing root mean square values of line-to-neutral voltages, line currents and active power per phase.

Similarly, the R.M.S. line currents are calculated taking into consideration the transformation ratio of current probes A_I and the number of turns at the clamps *turns*:

$$\tilde{I}_i = \sqrt{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} i_i^2(t) \cdot dt} \overset{\tau = \frac{T}{N_T} = \frac{k \cdot T}{k \cdot N_T} = \frac{t_2 - t_1}{k \cdot N_T}}{\Rightarrow} \ldots \Rightarrow \tilde{I}_i = \frac{A_I}{turns} \cdot \sqrt{\frac{1}{N_T} \cdot \sum_{i=1}^{N_T} i_i^2(i \cdot \tau)} \quad i\text{=a, b, c}$$

(3)

Respectively, the active powers per phase are calculated taking into consideration the respective transformation factors of the probes:

$$P_i = \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} v_i(t) \cdot i_i(t) \cdot dt \overset{\tau = \frac{T}{N_T} = \frac{k \cdot T}{k \cdot N_T} = \frac{t_2 - t_1}{k \cdot N_T}}{\Rightarrow} \ldots \Rightarrow P_i = \frac{A_V \cdot A_I}{turns \cdot N_T} \cdot \sum_{i=1}^{N_T} v_i(i \cdot \tau) \cdot i_i(i \cdot \tau)$$

i=a, b, c (4)

The apparent power S_{tot} and the active power P_{tot} are calculated using the following equations:

$$S_{tot} = \sum_{i=a,b,c} \tilde{V}_i \cdot \tilde{I}_i \qquad (5)$$

$$P_{tot} = \sum_{i=a,b,c} P_{in-i} \qquad (6)$$

These calculations are used on the converter input and output measurements.

More parameters are then calculated. These are the power losses at the converter P_{conv_losses}, the supply power factor $\cos\varphi_{\text{supply}}$ (ignoring harmonic influences) etc:

$$P_{conv\_losses} = P_{tot\_in\_inverter} - P_{tot\_out\_inverter} \quad (7)$$

$$\cos\phi_{\text{supply}} = \frac{P_{tot\_in\_inverter}}{S_{tot\_in\_inverter}} \qquad (8)$$

3.3 Equipment of the experimental system

The experimental setup has been developed in the Electric Circuits Laboratory of the Hellenic Naval Academy.

The parts used are the following:

- a Lab-Volt EMS 8821-13 three-phase power supply with a variable output of 0 ÷ 380V via auto-transformer, 3A/50Hz and a circuit breaker. This represents the constant voltage supply of the motor.
- a Lab-Volt EMS 8821-05 three-phase squirrel induction motor with 175W mechanical power, 380V, 0.52A, 50Hz, 1360rpm.
- a Lab-Volt EMS 8219-00 electrodynamometer with 0÷3N·m torque and 0÷3000rpm rotational speed. The power supply of the excitation supply is: 220÷240V, 50Hz, 0.9A via a four-diode rectifier. It represents the mechanical load of the motor.
- a HIOKI 3404 digital rpm counter with a measurement range of 30 ÷ 99.990rpm.
- a MITSUBISHI FR-E540-0.4K-EC AC/DC/AC converter, with 0.4kW active power, 400V (380V÷480V) at 50/60Hz three-phase input voltage with permissible AC voltage fluctuation 325 to 528V and frequency ±5%, rated output capacity 1.2kVA at 440V, three-phase output voltage 400V (380÷480V) at 50/60Hz [7].

- twelve isolated 12Vdc/1A power supplies electronically stabilized and protected from overcurrent and overheat.

With this equipment another variable that can be calculated is the output load power P_{out}, which is related to the torque T_s and the mechanical rotational speed a as follows:

$$P_{out} = T_s \cdot \omega = T_s [\mathrm{N} \cdot \mathrm{m}] \cdot \frac{a\ [\mathrm{R.P.M.}]}{60} \qquad (9)$$

After that, the total system efficiency η, which is the ratio between the output load power P_{out} and the input power P_{in} can be estimated:

$$\eta = \frac{P_{out}}{P_{tot\_in\_inverter}} \qquad (10)$$

Even more variables can be calculated such as power saving, spectrum analysis, total harmonic distortion etc.

4 An indicative experiment

The steady state energy saving problem of a three-phase squirrel induction motor is studied in three cases:

- without power electronics converter (scenario 1),
- with power electronics converter, but without any special frequency regulation (output converter voltage frequency equals to 50 Hz) (scenario 2),
- with power electronics converter, with voltage-frequency regulation with respect to nominal output mechanical load (scenario 3).

The output mechanical load of electrodynamometer ranges between 0÷120W with 20W steps. The values of the 6 line-to-neutral voltages and 6 line currents of the three phases are measured with the data acquisition (DAQ) system, the rotor speed of the electrodynamometer with the HIOKI 3404 digital rpm counter and the torque with the electrodynamometer’s indicator. The results are summarized in the following Figures 9 and 10.

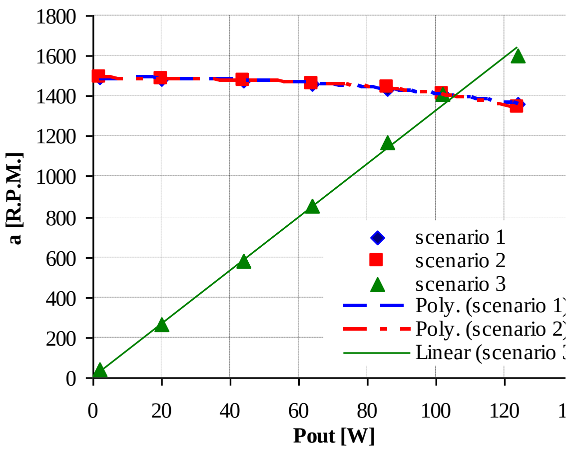

Figure 2. Mechanical power load P_{out} vs motor speed a, for (1) without power electronics converter, (2) with power electronics converter without frequency regulation, (3) with power electronics converter and voltage-frequency regulation.

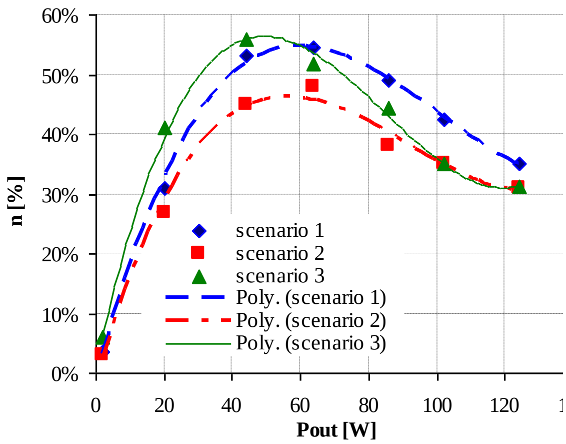

Figure 3. Mechanical power load P_{out} total motor efficiency η, for (1) without power electronics converter, (2) with power electronics converter without frequency regulation, (3) with power electronics converter and voltage-frequency regulation.

From the results, it can be derived that the total system efficiency is worse when a power converter is used without any frequency regulation. When voltage-frequency regulation is used, the total system efficiency is better for small mechanical load. That is because the losses of the converter harmonics are smaller than the power losses of the motor operating at its nominal slip point.

5 Conclusions

DAQ devices are invaluable instruments for recording and utilization of large amounts of measurements, when studying the transient and steady-state behavior of electric equipment. Especially in the modern warships, which become more and more all-electric, it is of particular interest to record simple parameters, like currents and voltages. From them more values, like efficiency, can be calculated. This way, equipment can be operated at low cost and its reliability can be increased.

6 Future steps

In the future the following will be implemented:

- The measurements of the mechanical load and the rotor speed will be added to the data acquisition system. This way all necessary measurements will be recorded simultaneously, increasing precision.
- The measurements of the voltages and currents can be utilized for the study of the supply's and motor's harmonic behavior.
- The transient phenomena will also be studied in different scenarios and energy saving results will be produced for different operating periods of the motor and variable torque profiles.
- The measurement process will be enhanced with emphasis to parameter calibration, such as sampling rate etc.
- The measurement system will be programmed to automatically be self-calibrated to the bias values and the actual transformation rations of the voltages and the currents probes.

7 Acknowledgements

The authors would like to thank Dr. I.K. Hatzilau, Emeritus Professor at the Hellenic Naval Academy, for his overall contribution to the configuration of the Electric Circuits Laboratory at the Hellenic Naval Academy.

Nomenclature

DAQ: Data AcQuisition system

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