IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

IMPROVED
INDUCTION MACHINE
TORQUE OBSERVERS AND VIRTUAL LOADING IN INDUSTRIAL APPLICATIONS, BASED ON REAL-TIME EMBEDDED CONTROLLERS

PhD Thessis – Summary

for obtaining the Scientific Title of PhD in Engineering
from
Politehnica University Timișoara
in the Field of Electrical Engineering
by

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Introduction

Nowadays, industrial equipment plays a crucial role in all industries. From measuring sensors to the most advanced control and supervisor complex systems, industrial equipment represents the foundation in all kinds of applications, from very small applications (such as small pumping groups, fans, machine condition, etc.) to very large applications (such as petroleum stations, the chemical industries, naval and aerospace factories, etc.).

The aims of this first chapter are dedicated mainly to justifying the need to utilize industrial equipment on a larger scale in as many industrial applications as possible and the expansion of their classical role with the development of processing capacities.

Besides the primary role of this real-time signals collection and monitoring system, in recent years, the need for a SCADA system also came as a requirement to increase efficiency, reduce system downtime, record errors, to facilitate communication with other equipment (pumps, sensors, fans, complex equipment, Human Machine Interfaces (HMI), etc.) and to actively participate in smart decision.

With high computing capability, the PLCs represent a crucial component of SCADA systems. They are worldwide spread and used due to their characteristics: they are stable against vibration, temperature, and dust and require low human resources for maintenance. Nowadays, PLCs can run complex tasks using dedicated functions, either integrated into SCADA systems or individually. As the main controller, the PLCs can have a complex centralized or decentralized structur. Nowadays, PLCs represent a central element of all industrial automation and have become an essential part of more and more applications [1],[2].

Observers design – a survey

In many industries, sensorless control represents a valuable achievement thanks to its potential benefits. More than that, in safety-critical applications, the redundant character is often achieved through multiple "parallel" connected sensors. In the last decades, the trend has been to replace at least one of those sensors with a sensorless monitoring device.

Sensorless monitoring methods were extensively investigated in all domains in response to the need for cost reduction.

In electrical machine control, the electrical machine state could be monitored by sensors (such as encoders or torque transducers) or by speed or torque estimators (observers/filters). There are several types of observers based on their principle of operation (Classical observers: Output based observer, Input based observer, Basic non-linear observer, Proportional-Integral

Observer, Luenberger observer; Disturbance Observer: Disturbance observer, Unknown Input observer, Perturbation observer, Extended State observer; Modern Observer: Kalman Filter, Extended Kalman Filter, H_infinity; Advanced Observers: Artificial intelligence based observer) [3]–[6].

Electrical machine virtual testing

Electrical machine testing is required for preliminary design checks and batch performance validation. Moreover, the electrical machine thermal testing represents a validation of the ventilation system and the insulation quality and confirms the machine's performance.

With the development of power electronics, electric motors' "standard" regenerative testing procedure was mainly done in a back-to-back configuration.

In many cases, the classical approach of electrical machine testing can be a high-time-demanding procedure not only due to the testing procedure but rather because of the need for mechanical coupling between the machines. In the case of large or vertical-mounted shaft machines, the shaft loading procedure can be very expensive or even impossible.

The virtual loading procedure for electrical machines presents a high demand in all industries (electrical machine design, production, and system integration), especially where the mechanical or electrical conditions require special needs.

There are several types of virtual loading procedures that are proposed in the literature such as the mixed frequency loading method, current harmonic injection method, dynamic thermal loading, and multiphase machine artificial loading [7]–[9].

In addition to all previously mentioned information related to artificial loading methods, the author proposes a new electrical machine synthetic loading method.

Twin induction machines without mechanical coupling driven by two dc-connected variable frequency converters are presented as the main parts of the new artificial loading method.

The solution allows machine testing for up to 120% of RMS phase current, with a power source twice smaller than the power source used for one single induction machine artificial testing [10].

Active torque pulsation reduction techniques in pulsating loads

Active Vibration Control (AVC) represents a well-known in-literature technique used in many domains, from seismic compensation to marine ships and noise canceling.

The AVC principle relies on a simple assumption that by adding force into the system in the opposite manner, equal or smaller in amplitude than the perturbance force, the sum of both forces (perturbance and newly added one) should have a smaller overall influence on the system than the disturbance alone.

In practice, there are different sources and types of torque pulsations in electric machines or electromechanical systems driven by electric machines. Regardless of the torque pulsation source, vibrations, noise, faulty positioning, and even mechanical failure are counted among their negative effects. The torque pulsation of a system represents one of the leading factors for mechanical system failure.

Torque smoothening is highly recommended in pulsating torque applications. Among the load torque filtering methods (thus reducing the created vibrations and other negative influences), passive smoothening methods are related to the utilization of the high mass inertias mounted on the same shaft as the load. One of the most used practical applications of high-mass flywheels is given in low-frequency recuperative energy storage systems (RESS).

The author presented idea regarding the torque pulsation reduction principle is related to a novel pulsation reduction method applied in the electromechanical system with position-dependent loads. Compared to literature solutions, this method is based on a position-dependent load driven by a grid-connected induction machine with an additional on-shaft small power machine driven by a variable frequency converter.

Based only on three currents and three voltages, an electromagnetic torque estimator is used for online real-time grid-connected induction machine torque estimation. The theoretical solution implies that the additional machine counteracts the pulsating load according to the system speed, using only information from the grid-connected induction machine that drives the load. Based on that value, the additional machine's drive is being controlled.

Standard low-cost industrial equipment – scope broadening

Over the last few years, one of the industry's significant trends was integrating compact industrial equipment into all applications. From research and education processes to safety and hardware-in-the-loop applications, PLCs have found their place in all industries: health and medical, wastewater treatment, construction sector, power generation, and management. In more complex applications, where the PLC unit represents the main control core, special and dedicated devices are mainly used in sub-applications that require special running conditions. In electric drive systems, the maintenance process is a key factor for saving time and money [11]. Real-time monitoring of system health status is an essential factor in all applications.

In case of variable (random) sample frequency it is mandatory that each action was taken in one interval to be computed based on the time interval since the last sample. In signal processing and analyzing, this issue represents one of the standard problems.

In literature, as the most straightforward way (which requires a minimum computation effort), it is recommended to interpolate the non-uniformed sampled signal and then "resample" at a constant frequency rate.

For non-real-time applications, considering a high performances control unit, using this method could be a practical solution. But on the other hand, in real-time applications, with output updates every program cycle, the interpolation/resample process cannot be successfully implemented.

The standard low-cost PLCs have system-dependent fluctuations. This means that depending on high-priority operations or during communication activities, the program cycle can be triggered at different intervals.

The communication between the peripheral systems and the central unit represents another significant influence on execution time. Depending on the data volume to be exchanged, the program cycle execution is subject to considerable time deviations.

Fig. *1* shows a practical example of time variation in PLC. Even if the execution time setpoint is set to 1 ms, the following figure shows an execution time average of 0.9086 ms. More than that, in this case, the maximum deviation time between two successive executions represents almost 19% of the execution setpoint.

As presented in the next figure, the inconsistent time variations make PLCs' utilization challenging for high-speed real-time, high-performance torque estimation applications.

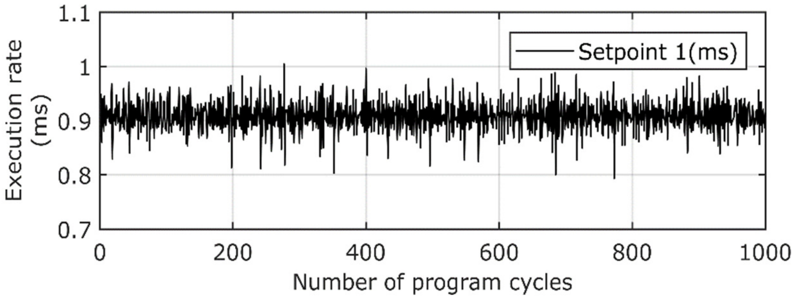

Fig. 1 Example of execution rate variations for one low-cost PLC 1ms execution rate setpoint

Some improvements can be achieved by measuring the elapsed time between two successive calculus and using it as a variable in the integral structures. The triggered time function produces an even greater central processing unit (CPU) loading.

Besides the previous investigation that proves that a low-cost PLC can not be used as a high-performance induction machine torque estimator due to the inconsistencies in acquisition and processing rate, next, the fundamental theory, as well as the experimental results, are given to use a standard low-cost PLC for frequency spectrum analysis based on well-known Fast Fourier Transform [12] for discrete-time (Discrete Fourier Transform DFT).

In machine condition monitoring and predictive health monitoring (MCM&PHM) systems, the presence or absence of a specific frequency from the frequency spectrum of a measured signal (voltage, current, vibration, speed, etc.) could represent the presence of a faulty part in the system.

The need for frequency spectrum analysis for system fault detection could represent a time and money-saving practice. An initial spectrum analysis could lead to preventive maintenance, thus reducing system downtime. Generally, the frequency spectrum analysis can be done online with specialized equipment or by measuring signals and offline process data with dedicated software.

The Cooley-Tukey algorithm represents one of the most popular Fast Fourier Transform in discrete time. Because it requires low data resources and it consists of non-complex data operations, the Cooley-Tukey algorithm is widely used for DFT implementation.

There are a lot of Cooley-Tukey's algorithm versions based on different approaches to data processing. The method is used for data arrays with complex elements of lengths equal to the powers of 2 for maximizing the method's efficiency [13]. This method divides the input data array into two equal parts.

The method consists of combining these two equal parts taking the elements two-by-two and then multiplying them with the appropriate unit root, which also represents the twiddle factor. There are two possibilities to perform DFT: Decimation-in-Time (DIT) and Decimation-in-Frequency (DIF). Both algorithms perform $N \cdot log_2 N$ calculus, where N represents the total length of the input array.

Industrial equipment-based line-start IM torque estimation with experiments

In general, suitable control devices should be used depending on the application type (critical application, health application, etc) and application specification (time response, acquisition frequency, output update time, etc.).

In more complex applications, where the PLC unit represents the main control core, special and dedicated devices are mainly used in sub-applications that require special running conditions. In electric drive systems, the maintenance process is a key factor for saving time and money. Real-time monitoring of system health status is an important factor in all applications [14].

The testing bench (Fig. 2) consists of two coupled induction machines: the grid-connected one with three-pole pair (delta connection), 11kW named the main motor (MM) and the Variable Frequency Converter (VFC) driven one with two-pole pair, and 15kW rated power.

The PLC unit is used for real-time control of the loading machine: prescribes the load model to the ELM. The cRIO-9086 platform reads all the necessary electrical data for IM's torque estimation. The torque estimation process can be done offline or online (on FPGA).

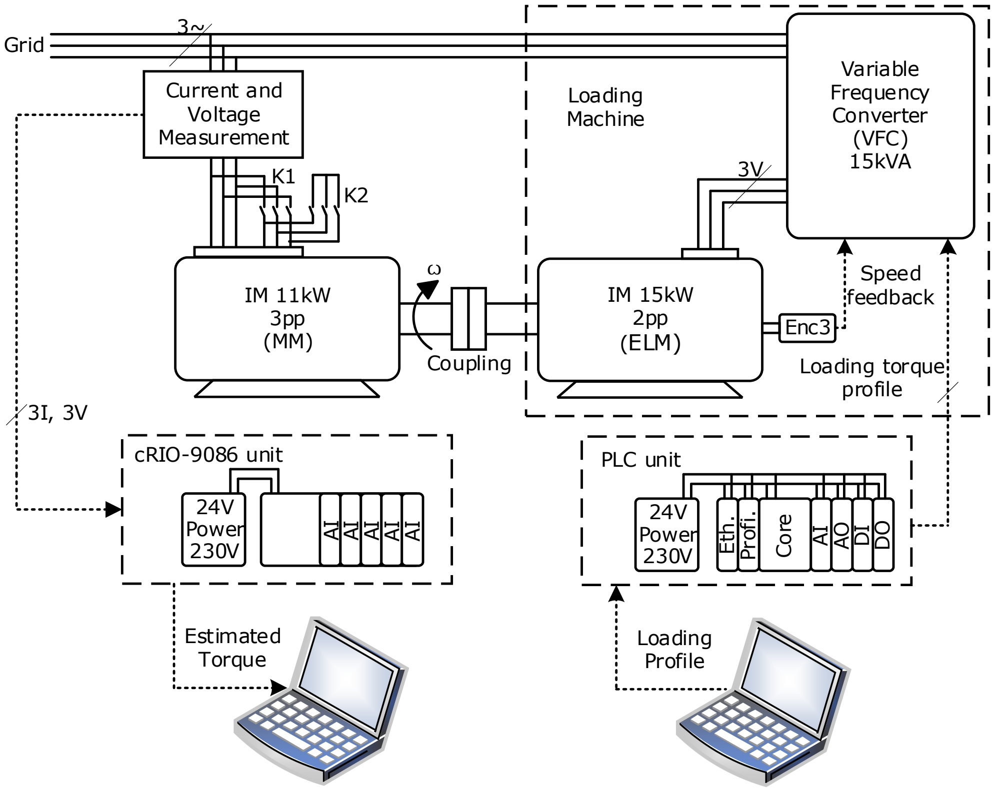

Fig. 2 Experimental setup for induction machine torque estimation

Three torque estimators (Luenberger observer, The direct torque computation method and The dynamic torque computation method – which is based on the Induction Machine model that was used for simulations) are simulated and then experimental studied in order to perform the real-time induction machine torque estimation.

The simulated results are given when the Induction Machine is supplied with an ideal three-phase voltage source. The IM is also simulated also when the three-phase voltage system reproduces the real three-phase voltage characteristics.

In order to achieve a more accurate average of the relative harmonic content and to reproduce the influences of inverse components more accurately, the on-site three-phase voltage system that supplies the real IM has been measured over several days at different times of the day. The acquisition frequency presents a significant influence on the accuracy of IM simulations.

Fig. 3 shows the simulated IM's electromagnetic torque when the machine is supplied with a three-phase voltage system without harmonics or inverse components, but during the acquisition process, the acquisition frequency was modified randomly (in order to simulate the inconsistency in acquisition frequency). Based on acquisition time variations even a decent low-cost PLC shows a cyclic time variation greater than 6% of the set time.

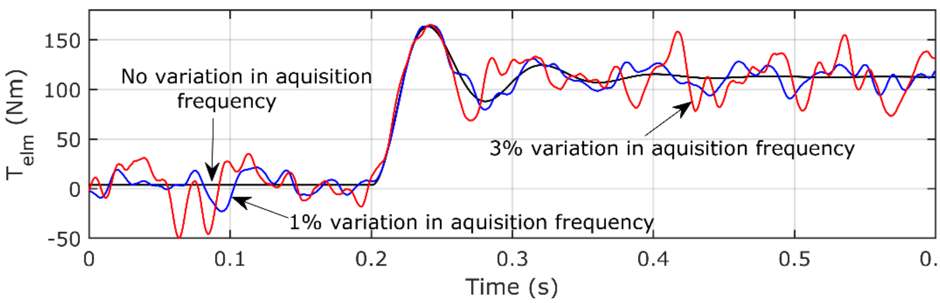

Fig. 3 The influences of the acquisition time variations over the IM operation

It can be seen that with only a 1% variation of the acquisition frequency (blue graph) the IM has an unstable operation, while with a 3% variation of the acquisition frequency (red graph), the electromagnetic torque varies in steady-state even by more than 50% of its mean value.

The following figure shows the comparative experimental results of the three estimators (Luenberger observer, direct computation method, and dynamic method) in response to a step signal prescribed to the loading machine. At rated load, in steady state, the dynamic method produces a phase-shifted electromagnetic torque compared to the Luenberger observer, while the direct computation method shows the smallest torque ripple despite the speed estimation limitations. No significant differences between estimators are observed during the transient regime.

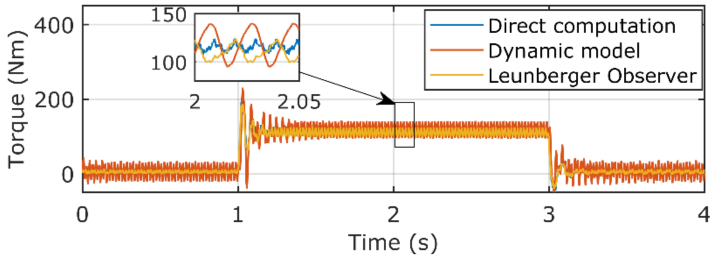

Fig. 4 Torque estimators no-load to rated power transition

PLC-based IM virtual loading

This chapter presents an artificial loading method of two induction machines (IM) without mechanical coupling using two dc-link connected variable frequency converters (VFC). Industrial standardized inverters, control equipment, and communication protocols are used.

The following artificial loading approach assumes a rated current IMs loading via fast operating mode switching (motor mode to generator mode and generator mode to motor mode). The overall human resources cost reduction and the lack of mechanical coupling between the induction machines represent the most significant advantages of this procedure. On the other hand, the method requires the employment of two identical machines and two identical dc-connected variable frequency inverters, which is one of the system's most significant drawbacks. Furthermore, testing two machines simultaneously might be considered a time and cost-saving method. In literature can be found several methods of electric machines' artificial loading [15].

Injecting the oscillating power into the grid could be a feasible option, but a bidirectional ac-dc-ac inverter costs about the same as two unidirectional inverters in the case of conventional industrial inverters. Furthermore, in the case of a weak power grid, high power oscillations from and towards the grid have a negative impact on grid voltage (voltage oscillations causing light flicker or inappropriate functioning of other equipment) [16].

Fig. 5 presents the setup configuration used for the artificial loading test. Two standard industrial dc-connected variable frequency converters are used (VFC1, VFC2). This way, PLC-VFCs communication uses standard industrial protocols. No additional changes were made to the VFCs operation principle. Two identical three-phase induction machines are directly connected to the inverter side of the converters. The VFC1 drives IM1, while IM2 is driven by the VFC2. The induction machines are not mechanically coupled. No position or speed encoders were used in this artificial loading method.

Considering the induction machines' star connection and the use of the VFC is highlighted that during the artificial loading procedure, the notably circulating currents that flow through inverters do not contain 3k (k=0,1,2..) harmonics nor notably fifth and sixth harmonics.

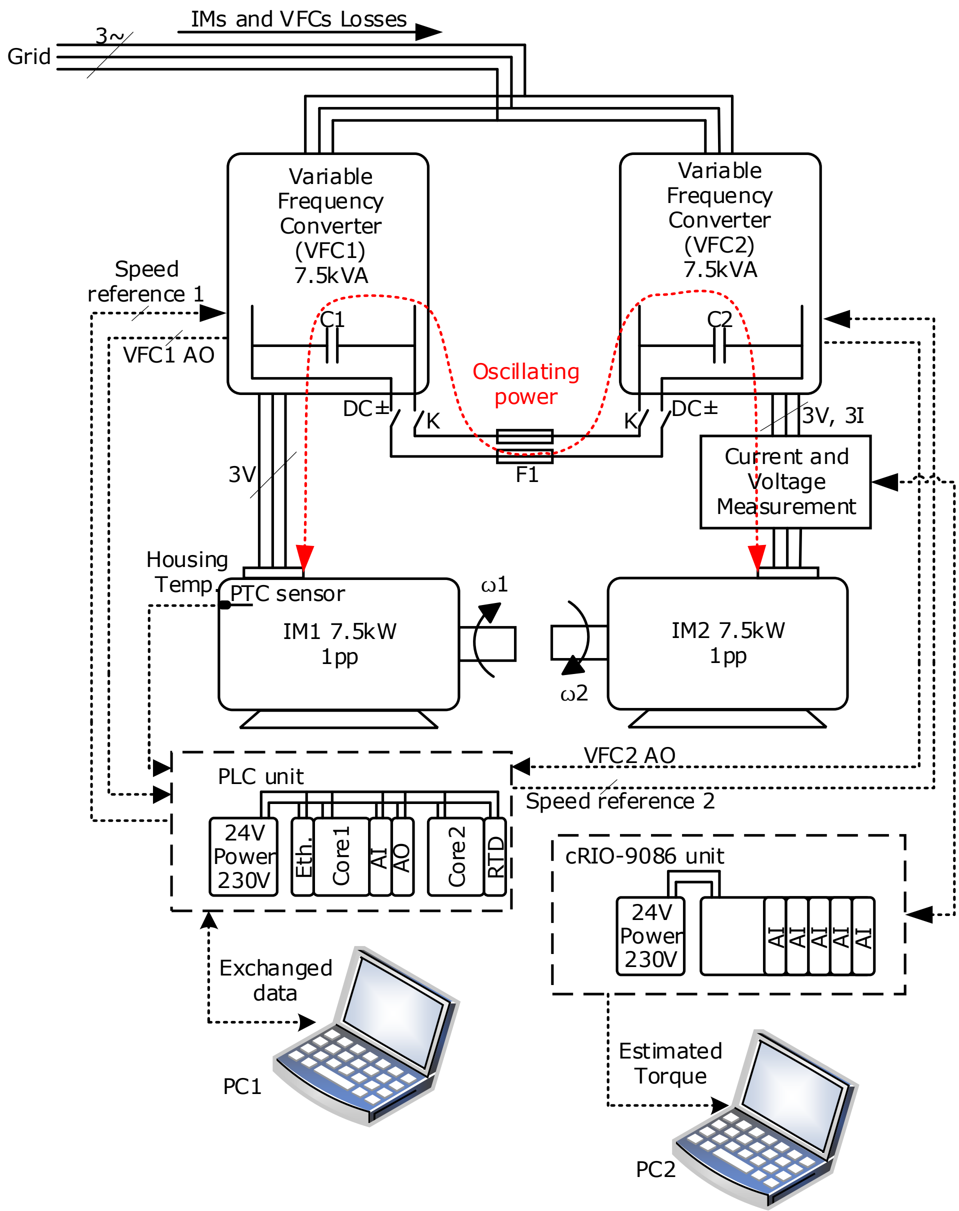

Fig. 5 Experimental setup – diagram representation (two induction machines driven by two dc-interconnected variable frequency converters)

Only industrial/commercial equipment and standardized communication protocols are used for this artificial loading method, where two induction machines without mechanical coupling are tested at rated phase currents. When one IM accelerates, the other one decelerates. The power flows from one IM to another via the common VFCs dc-link.

Several ways to change the IM RMS current are given: either by changing the speed reference amplitude or changing the speed reference frequency. During all these tests, the speed dc offset was set at 2500rpm inside the VFCs. The VFCs current limit is 130% of IM-rated current (about 20.5A).

For ac-source current limitation, different speed references were investigated: 180-degree phase-shifted - where both references were fixed-time shifted, variable phase shift - where the IM in motor mode was delayed from accelerating, and triangle reference - where the IM was forced to change faster the operating regime.

For artificial loading speed references, an open-loop or a closed-loop method can be used. The thermal test, presented in Fig. 6, represents the practical applicability of the closed-loop automatized start-loading-stop procedure.

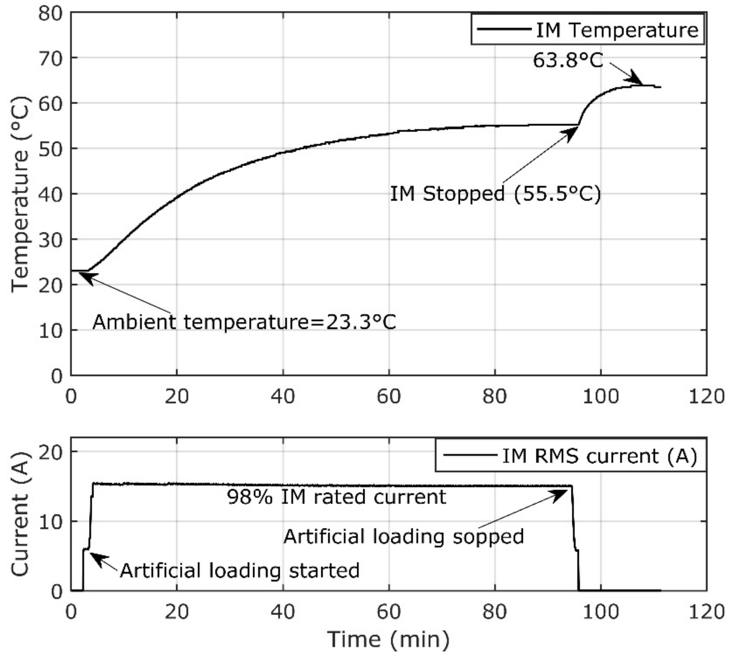

Fig. 6 IM temperature (measured in the lifting hook) and the IM RMS current at 2500rpm with ±500rpm amplitude and 6Hz oscillation frequency

Active torque pulsation reduction in position-dependent loads

The active vibration control (AVC) technique is represented by the use of an external force added into the system, in the opposite manner to the disruptive force (the source of the main vibrations), to reduce partially/totally the unwanted effect of vibrations.

Another modern AVC applicability can be found in robot applications, where vibration-free positioning plays a key role in increased accuracy [17].

As a particularity, in headphones, active noise canceling (ANC), which is -more or less - based on the same principle as AVC, has been adopted by all the major vendors. In this case, active noise canceling (ANC) is pretty similar to AVC because, in this case, the additional force added into the system is replaced by the sound/noise (which should be eliminated) measured outside the headphones and then is reconstructed inside the headphones to eliminate the unwanted distracting background noise [18].

One of the simplest methods for torque pulsation reduction in electromechanical systems with rotating electric machines is represented by the use of passive mechanical methods: flywheels.

This chapter deals with the torque pulsation reduction methods for position-dependent loads (such as reciprocating compressors) driven by grid-connected induction machines. Compared to the literature presented solutions, the here-presented method is based on an auxiliary motor driven by a VFC, mounted on the same shaft as the load (Fig. 7).

Moreover, the here-presented torque pulsation reduction method implies a relatively simple control technique compared to the repetitive control. As the main difference, the solution is presented as a mechanical parameters-free solution, where only the moment of inertia is required for active torque pulsation damping.

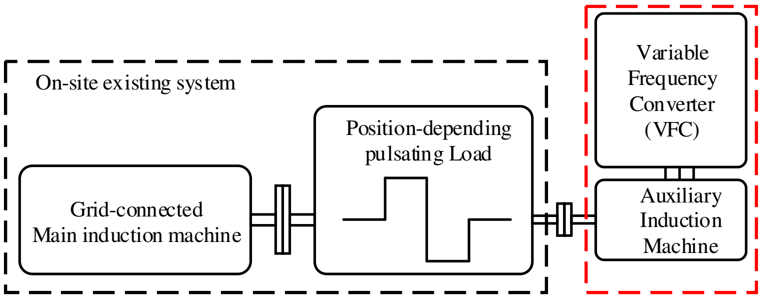

Fig. 7 Basic schematic diagram of the proposed operating principle

The results from the active torque pulsation reduction method (ATPRM) from the open-loop control system are presented in Fig. 8. Here, the experiment is divided into five sectors. Between 2s and 5s, the loading torque follows a 70%dc + 30% sinusoidal component (of GCIM-rated power). Until the ATPRM is applied, the auxiliary machine is only mechanically connected to the system without torque prescription (only inertia moment influences). From 3s to 5s, the open-loop ATRPM is applied. In sector 3s-4s, the auxiliary machine produces a 180-degree phase-shifted (considering GCIM torque) sinusoidal torque to the respected angle. In sector 3s-4s, the auxiliary machine compensates for 14% of GCIM-rated torque, while in sector 4s-5s, the auxiliary machine compensates for 17% of GCIM-rated torque. Acceptable results are obtained regarding torque pulsation minimization in the grid-connected induction machine. However, a certain level of torque pulsations appeared in the auxiliary machine.

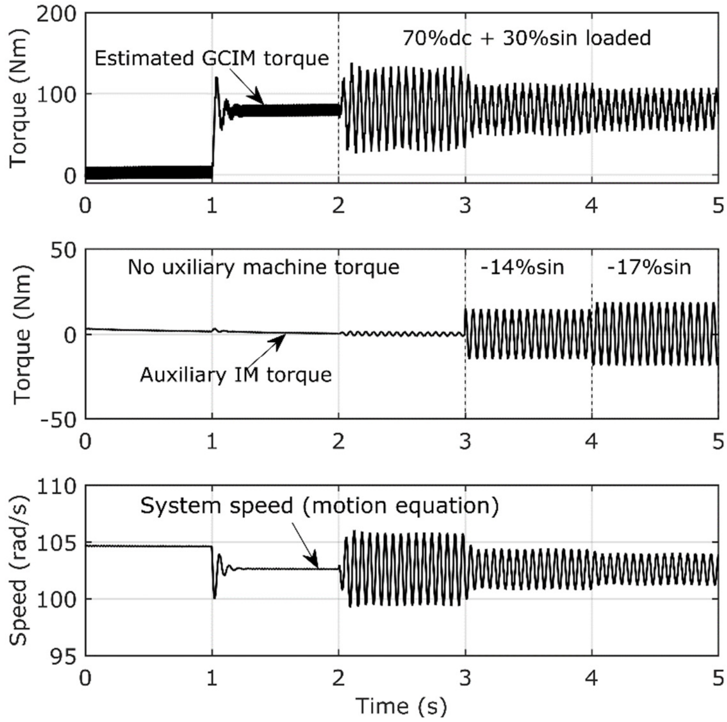

Fig. 8 Estimated GCIM torque, auxiliary IM torque, and system speed for open-loop control method with no aux. compensation, with 14% (GCIM-rated power) compensation and 17% (GCIM-rated power) compensation

Considering that the targeted position-dependent loads do not change their loading angle a two-step method was proposed for the preliminary detection of the system's total moment of inertia and loading torque. Simulation and experimental results are given for different frequency spectrums of the loading torque. The experimental setup limitations are highlighted for complex loading torques composed of the first three harmonics. Fig. 9 presents the torque reference given by the PLC to the VFC, the actual loading torque produced by the VFC (both read from the variable frequency converter that drives the loading machine) and the resulting torque obtained after the two-step method was appliend.

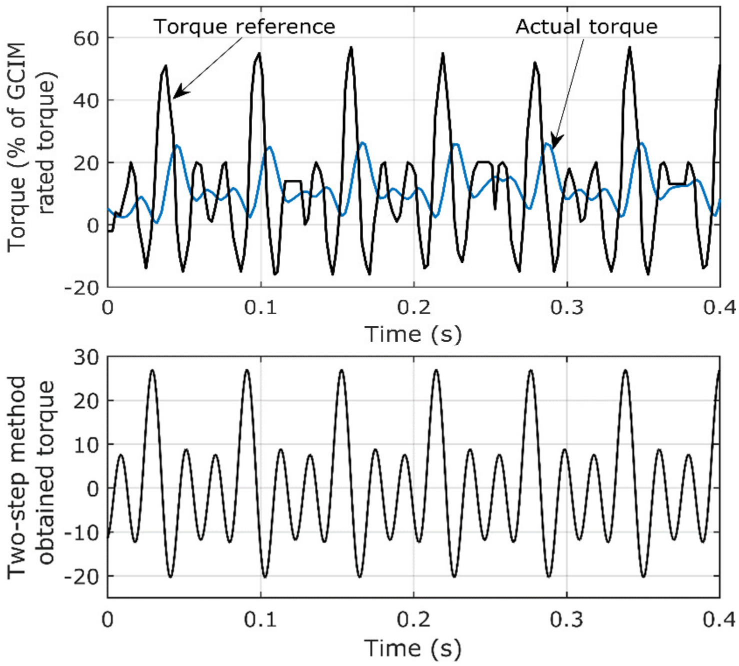

Fig. 9 Loading torque reference prescribed by the PLC to the load VFC, the actual torque produced by the VFC an the reconstructed loading torque from the two-step method

Conclusion, contribution, and future work

Conlcusion

This thesis had as its main purpose the study of the possibility of extending the classic role of industrial command and control equipment. In this context, using classic industrial equipment, three different applications are presented, simulated, and experimentally validated. To extend the main traditional role of the Programmable Logic Controllers (PLC), three different low-cost PLCs were extensively investigated to be used as grid-connected induction machine electromagnetic torque observers. It was proven that the main factor that has to be considered for this type of application is not represented by the acquisition frequency but by the variation of the PLC's program cycle.

An artificial (synthetic) loading procedure was proposed for two identical induction machines without mechanical coupling driven by two identical dc-link connected, unidirectional variable frequency converters. The phase-rated current loading and thermal test can be performed with industrial standard equipment. No overvoltages occurred even at 120% of the rated current. The experiment revealed that the induction machines' efficiency has a major role as long as the ac source current spikes are given by the machines' losses over a complete period.

For rotary electromechanical systems, acceptable results can be obtained regarding active torque pulsation reduction for position-dependent loading torque using a novel system configuration with a smaller auxiliary machine mounted on the same shaft. Although this configuration requires a third machine driven by a two-quadrant inverter, the auxiliary machine can successfully smoothen the torque alternating pulsations by producing a 180-degree phase-shifted torque compared to the loading torque. It was analytically demonstrated that the same configuration could be used in a two-step method for the system of inertia and loading torque detection. It was experimentally shown that the loading torque phase requires special attention for effective compensation. The two-step method can also be used for complex loading torques with harmonic content and phase shifts different from 0 degrees. The total system moment of inertia gives the loading torque frequency limitation.

Contribution

The main contribution are summarized bellow:

- The PLC implementation of three different electromagnetic torque estimators and the Discrete Fourier Transform based on the Cooley-Tokey Radix-2 algorithm.
- The simulation, both for ideal data and ideal data with real characteristics, all three torque estimators: the direct computation method, the dynamic torque computation method, and the Luenberger-based torque observer.
- Creating a Labview dedicated algorithm (FPGA+RT programming mode) for the cRIO-9086 platform for online investigation of all three torque estimators, including also the Modbus TPC communication procedure and the high-speed reading of the incremental encoder TTL-type signal.
- Proposing a new twin un-coupled inverter-fed induction machine artificial loading methodology with comprehensive modeling analysis and testing validation.
- Simulating and experimental validating the proposed active torque pulsation reduction method both in theoretical and practical situations.
- Proposing, testing, and experimental validating of a novel mathematical two-step tool based on the current solution with an auxiliary machine mounted on the same shaft for preliminary system moment of inertia and loading torque detection procedure.

Future work

Further investigations are needed regarding:

- A suitable low-cost with minimum-performance PLC that can be used successfully for torque estimation based on traditional observers is needed.
- New torque estimators suitable for low-cost processors with small cyclic time variations.
- Loss estimation improvement for the artificial loading method, also considering the reference speed of the artificial loading procedure (sine, triangle, phase-shifted sine).
- Creating a lookup table-like dataset for experimental setup time delays used to reduce the two-step method's errors.
- New torque pulsation reduction strategies can be developed considering the maximum stress on the mechanical couplings also.

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