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An Approach on a Transient Regime of a CNC Machining Center Spindle Drive System Using the Active Electrical Power Evolution

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Abstract
This paper proves in theoretical and experimental terms the availability for scientific research of the active electrical power absorbed by a CNC machining centers during a transient regime of the spindle motor (start/stop on 10,000 rpm) electrically supplied by an AC/AC converter. A simple computer assisted experimental setup (with transformers placed on the electrical supply system of the converter, signals acquire system) and processing procedures are used in order to produce a correct approach of spindle motor and converter behaviour concluded in condition monitoring and diagnosis. Some relevant results were obtained in description of active electrical power (energy) absorption during acceleration and negative power absorbed during deceleration by electrical braking, in the description of instantaneous power constituents (voltage and current) and evolution in frequency domain by fast Fourier transform. An experimental approach on energy conversion efficiency (converter input electrical energy into output mechanical energy of spindle motor) was done. As an interesting topic for future, these research achievements are available in the research of mechanical loading (torque) during cutting processes (cutting tool and process condition monitoring).

Keywords
CNC machining center, spindle motor, transient regime, active electrical power, monitoring

1. Introduction

The behaviour of the spindle motor currently used on a CNC machining center (the spindle being also the rotor of a three phase AC motor) and the driving system (an AC/AC converter) during a transient regime without external loading (start/stop regime) is an interesting item in experimental research. This behaviour indicates first if the spindle motor and the AC/AC converter work properly and describes their condition (rotational dynamics for spindle and electrical phenomena for motor and converter). The behaviour during the steady-state regimes (with constant rotational speed of the spindle) is also an interesting topic (e. g. related by internal mechanical loading, due to the dry and viscous friction).

One of the best ways to solve this issue is to use a monitoring system based on the evolution of active electrical power (AEP) [1, 7] absorbed by spindle motor through the AC/AC convertor [2, 6]. For the spindle running without any external loading (e.g. a cutting process) the absorbed AEP is mainly converted firstly in active mechanical power (AMP) and after transformed into heat (due to the friction phenomena). A part of AEP is directly converted in heat inside the motor and AC/AC converter. During a cutting process a supplementary part of the absorbed AEP is converted in AMP. This supplementary part of AEP describes the loading of spindle motor (torque and angular speed) or the interaction between a cutting tool and a working piece as well [3, 4, and 5]. In this situation the spindle motor is used as natural sensor for mechanical loading during a working process (as a future approach and major challenge) if the absorbed AEP during steady-state regime without external loading (supposed to be constant) is known. Actually the new CNC machining centers has some built-in features for AEP monitoring used currently as a summary mechanical loading level indicator, exploitation tracking and for maintenance purposes. Unfortunately these features are not accessible for experimental research in the terms of this paper.

The AEP monitoring system proposed in this paper requires a very simple experimental setup (a voltage transformer, a current transformer, a data acquisition system, and a computer) and some computer assisted signal processing procedures for AEP calculus.

This paper is focused on experimental research of a transient regime on a vertical CNC machining center Okuma Genos 450-V [8]. This is a preliminary approach for a future study extended to cutting processes monitoring or other working processes driven with AC/AC (or AC/DC) convertors and motors as well (e.g. elevators, robots, etc.).

The second section of this paper is a theoretical approach of AEP monitoring; the third section presents the experimental setup; the fourth section presents the experimental results and discussions; the fifth section is dedicated to conclusions and future researches.

2. A theoretical approach on AEP measurement

The AEP absorbed by an AC single-phase electrical supplied device (e. g. an electric motor running in steady-state regime) can be simply described if the electrical voltage $u(t)$ and the electrical current $i(t)$ at the input are known (e.g. by experimental computer aided measurement). The instantaneous electrical power (IEP) is the result of multiplication of the voltage and current:

$$p(t) = u(t) \cdot i(t) \tag{1}$$

Because the voltage and current are variable the IEP is a sum of two components. One of them is the AEP converted by the electrical supplied device in AMP and heat. The other component is a periodical constituent PC not related by AEP (it moves permanently between the power supply and the electrical supplied device). If the voltage and the current have sinusoidal waveforms (with $u(t) = U{\cdot}sin(\omega t)$ and $i(t) = I{\cdot}sin(\omega t\text{-}\varphi)$ as usually happens for electric motors) the AEP is the mean value of IEP calculated on each period T=$2\pi/\omega$. With n_1 numerical samples of voltage ($u[t_k]$) and current ($i[t_k]$, with t_k=$k{\cdot}\Delta t$ the sampling time) on the period T (supposed to be constant) the description of AEP is defined as [7]:

$$P[t_j] = \frac{1}{n_1}\sum_{k=1}^{n_1} p[\,t_k] = \frac{1}{n_1}\sum_{k=1}^{n_1} u[\,t_k] \cdot i[t_k] \tag{2}$$

The AEP sampling time t_j is defined as: $t_j = (j\text{-}1){\cdot}T + T/2$. If the sampling rate of current and voltage is $1/\Delta t$ than the sampling rate of AEP is $1/T$. By this procedure the PC part of IEP is completely removed.

The evolution of AEP can be also obtained if the PC is removed from IEP by low-pass numerical filtering. In this case the AEP sampling rate is increased up to $1/\Delta t$. A low pass filter with $1/T$ cut-off frequency removes efficiently PC especially when n_1 is constant (ω is constant). A simpler method to remove PC uses a moving average filter [9] with n_1 points in the average. The current sample of AEP is theoretically described as an average of n_1 previous values of IEP:

$$P[t_k] = \frac{1}{n_1}\sum_{i=1}^{n_1} p[\,t_{k-i}] \tag{3}$$

Here and above n_1 is the integer part of the ratio $T/\Delta t$ and $k \geq n_1$.

The IEP description from Eq. (1) and AEP from Eq. (2) and (3) are available also for a three-phase electrical supplied device. Usually the voltage and the current delivered on each phase are identical. In these conditions in both equations we should consider a multiplication factor equal with 3 (with the measurement of voltage and current done on a single-phase).

There are some particularities of AEP monitoring when a three-phase electrical network is used to supply a motor through an AC/AC converter. The voltage and especially the current (both measured on a single phase before AC/AC converter) are periodical but they have not pure sinusoidal waveforms (as Figures 6 and 9 shows here below). The AEP definition from Eq. (2) is perfectly available if the period T is evaluated on the voltage evolution. Now the IEP contains many periodical components (fundamentals and harmonics). If a $1/\Delta t$ sampling ratio of AEP is desired (the same with the current and the voltage) then the removing of these periodical components could be done as before with a low-pass numerical filter (with $1/T$ cut-off frequency). The using of a moving average filter (according with Eq. (3)) is not perfectly suitable because it eliminates completely only the periodical component with $1/T$ frequency and its harmonics (and attenuates all other bigger frequency components). In this situation a repeated moving average filter is required, each time with a number n_h of samples in average adapted to the frequency f_h of each fundamentals of periodical components (with n_h being the integer part of the ratio $1/(f_h \cdot \Delta t)$). This filter is described in Eq. (4). If $h = 1$ then $P_1[t_k] = P[t_k]$ with $P[t_k]$ defined in Eq. (3).

$$P_h[t_k] = \frac{1}{n_h} \sum_{i=1}^{n_h} P_{h-1}[\,t_{k-i}] \tag{4}$$

If h is high enough this repeated moving average filter works with a good approximation as a low pass filter with $1/T$ cut-off frequency.

3. Experimental setup

The experimental setup is conceptually described in Figure 1. The three-phase spindle motor SM is supplied by an AC/AC converter. This converter (driven by the CNC control unit) is supplied from a three-phase network through an AC/AC transformer. Between transformer and convertor a current transformer CT and a voltage transformer VT are placed (the wire of phase c works as primary circuit of CT, the primary circuit of VT is supplied between the phase c and the potential reference line $N=0V$). The output of CT (from its secondary circuit) is applied on a resistor with a small resistance (8 ohms). The voltage drop on this resistor is proportional with the current ($u_{ct}=k_c \cdot i(t)$) and is applied on the second channel (Ch 2) of a numerical oscilloscope (PicoScope 4424, PicoScope Technology [10]). The output voltage from the secondary circuit of VT is proportional with the voltage on phase c related to line N ($u_{vt}=k_v \cdot u(t)$) and is applied to the first channel (Ch 1) of the oscilloscope. The measurement of current and voltage on a single phase is acceptable (in order to calculate the AEP absorbed on phases a, b and c) supposing that (as normal) the current and voltage on each phase are the same (except a $2\pi/3$ phase shift difference between each two phases).

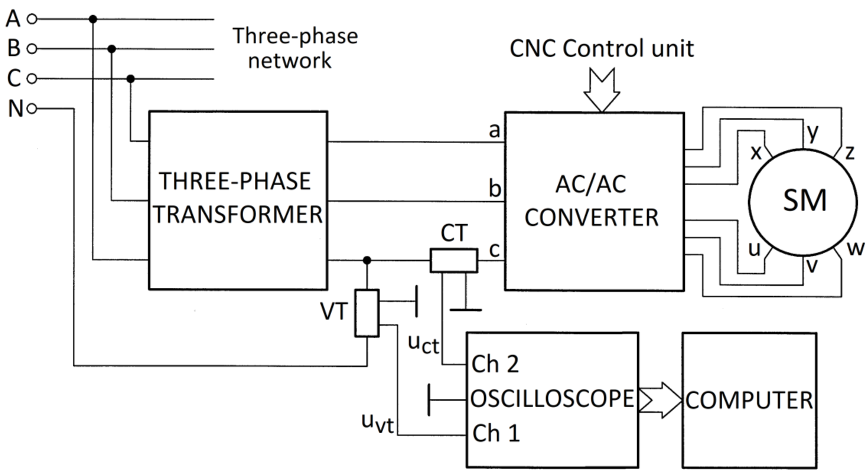

Fig. 1. A conceptual description of the experimental setup

Both signals (u_{vt} and u_{ct}) from oscilloscope input are converted in numerical format and delivered to the computer for calculus of IEP absorbed by AC/AC convertor and motor using Eq. (1) rewritten for a generic sample $p[t_k]$ as:

$$p[t_k] = 3 \cdot u(t_k) \cdot i(t_k) = \frac{3}{k_v \cdot k_c} \cdot u_{vt}[t_k] \cdot u_{ct}[t_k] \tag{5}$$

The description of AEP according with Eq. (2) becomes:

$$P[t_j] = \frac{1}{n_1} \sum_{k=1}^{n_1} p[\,t_k] = \frac{3}{n_1 \cdot k_v \cdot k_c} \sum_{k=1}^{n_1} u_{vt}[t_k] \cdot u_{ct}[t_k] \tag{6}$$

All the considerations related to AEP obtained by single or multiple filtering (Eq. (3) and Eq. (4) respectively) are available here. The product $k_v{\cdot}k_c$ has the value 0.000638 V/A (this value was experimentally confirmed by measuring the AEP absorbed by two single-phase electric calibrated devices (with known absorbed AEP).

Figure 2 presents a picture on current transformer CT placed on the phase *c* of AC/AC converter electrical supply network. Here also is observable the resistor placed on secondary circuit of CT and a connexion for voltage transformer VT. The literature [4, 6] uses three current transformers CT, and three voltage transformers VT, each one placed on a phase. We found that this is not necessary since the current and voltage on all phases are theoretically the same (except the phase shift between).

Figure 3 present a picture on CNC machining center and external setup components (oscilloscope and computer).

Fig. 2. A picture with the current transformer CT

Fig. 3. A picture with experimental setup components near the Okuma Genos 450-V CNC machining center

4. Experimental results and discussions

The transient regime evaluated with the procedures presented above consists of an experiment with a start/stop cycle for the spindle motor on 10,000 rpm. Figure 4 presents the IEP evolution during this experiment (lasting ten seconds). The u_{vt} and u_{ct} voltages are digitally acquired simultaneously with 100,000 s^{-1} sampling rate or $\Delta t = 10$ μs sampling time and 12 bits digital resolution.

There are clearly indicated the three main stages of this regime: start, steady-state and stop. Figure 5 presents a zoom-in detail during steady-state from area A. Here is indicated the semi-period $T/2$ (10 ms, which corresponds to the usual value of AC voltage frequency: 50 Hz). As expected there are many variable PC components. These components are generated because the voltage and current are not strictly sinusoidal (as Figure 6 shows, with the evolution of u_{vt} and u_{ct} voltages). These particular shapes of voltage and current are related by the AC/AC converter behaviour when the spindle motor rotates in steady-state regime (10,000 rpm). This topic is not relevant for this paper.

Figure 7 presents a description of IEP evolution (from area A on Figure 4) in frequency domain (obtained by fast Fourier transform). This describes the periodical components of IEP (with frequency and amplitudes), starting with a 50 Hz component and its odd harmonics (100, 200, 300 Hz, etc.) and some components around 5 kHz frequency.

We should mention that this spectrum is slightly modified because before the IEP calculus the voltages u_{vt}, u_{ct} are low pass filtered inside the oscilloscope.

In a first approach because the harmonic correlation of variable components from area B (Figure 7) is revealed, a single moving average filter seems to be able to eliminate or to reduce significantly this components in order to generate the AEP evolution from IEP already depicted in Figure 4. This filter (described in Eq. (3)) is designed related with 50 Hz frequency component (T = 20 ms, n_1 =20 ms/10μs = = 2000) and it removes completely all the components revealed before (the fundamental of 50 Hz and its harmonics). This filtering of the IEP depicted in Figure 4 produces the AEP evolution from Figure 8.

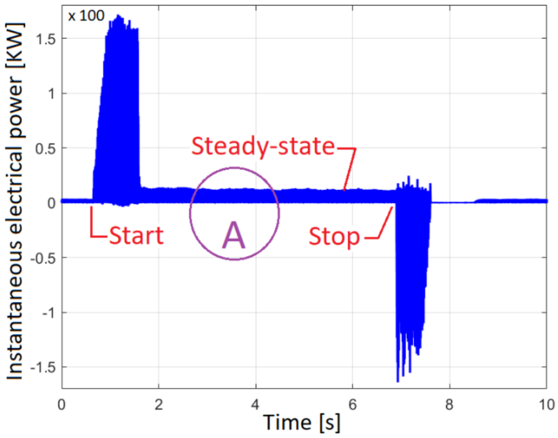

Fig. 4. The evolution of IEP during a transient regime (start/stop cycle on 10,000 rpm)

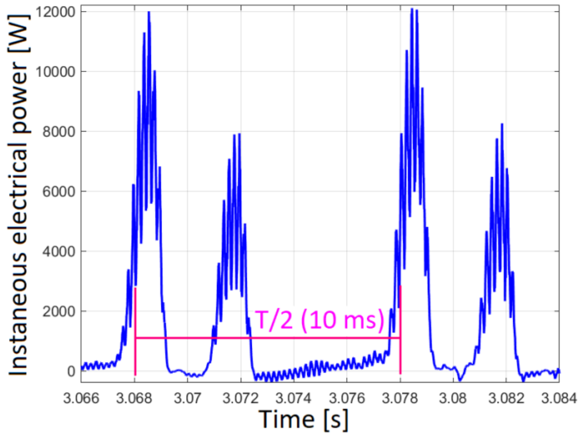

Fig. 5. A zoom-in detail on Figure 4 (on area A)

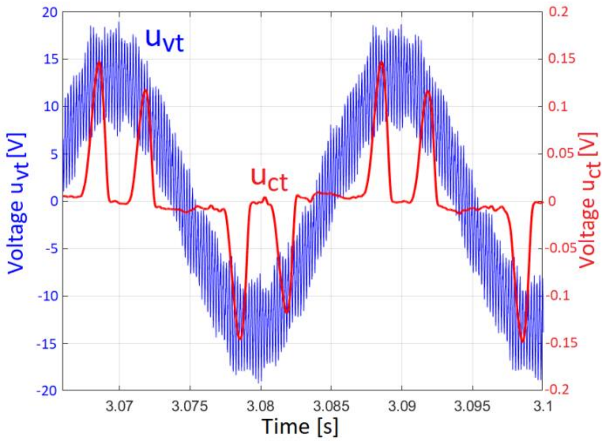

Fig. 6. A description of voltage (with u_{vt}) and current (with u_{ct}) at the converter input (on phase c) on area A from Figure 4

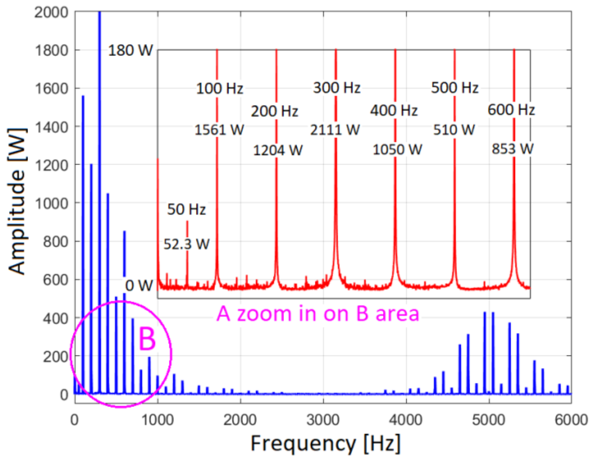

Fig. 7. A description of IEP in frequency domain in area A from Figure 4

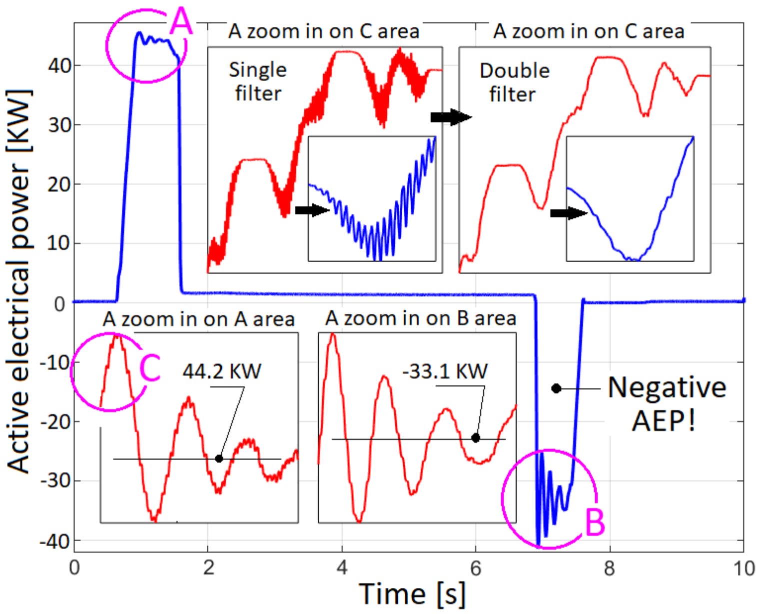

Fig. 8. The evolution of AEP during a transient regime of motor spindle (start/stop cycle on 10,000 rpm). The result of moving average filtering of IEP from Figure 4

The mirroring of transient regime in AEP evolution is evidently. The spindle motors accomplishes the increasing of speed from 0 to 10,000 rpm in less than a second. The big angular acceleration and spindle inertia generates a high dynamic torque. This dynamic torque multiplied with instantaneous angular speed defines an active mechanical power mirrored in the absorbed active electrical power evolution (below the area labelled with A) with an average value on the top level of 44.2 kW (the motor has 15 kW power). After this dynamic phenomena ceased a steady-state regime is installed. The motor stopping phenomena (in less than 700 ms) is described above the area labelled with B. The AEP suddenly drops temporary to a negative value (with an average value on the bottom level of -33.1 kW) because the AC/AC converter works as a dynamic braking system: the mechanical kinetic energy of the spindle (previously accumulated at starting) works as a mechanical active power supply for the motor (who works now temporarily as generator) which produces AEP delivered to the electrical supply network via converter and transformer (Figure 1). The negative value of AEP means the changing the direction of normal flow of power: now from motor to electrical supply network.

A zoom-in on C area of AEP signal (in top of Figure 8, left side) reveals that a single moving average filtering doesn't remove completely all variable components of IEP. There still remains some unfiltered high frequency components mainly grouped on 5 kHz frequency (already revealed in the spectrum from Figure 7). A second filtering is necessary, according with Eq. (4) with $n_2 = 1/(f_2 \cdot \Delta t) = 1/(5{,}000 s^{-1} \cdot 10 \mu s = 20)$. The result of this supplementary filtering is revealed in the second zoom in on C area (in top of Figure 8, right side).

An interesting behaviour is revealed in the areas A and B: a free viscous damped response of the elastic system of the spindle motor mirrored in AEP evolution (here are involved the spindle inertia, the stiffness of the magnetic field which rotates the spindle, the dry and viscous friction inside the motor). This will be a topic for a later research.

Figure 9 presents a detailed view on AEP evolution from Figure 8. This Figure is focused on steady-state area (the positive and negative AEP peaks from Figure 8 exceeds the drawing space of Figure 9). In A the motors starts to turn on 10.000 rpm. Due to dynamic torque it starts a strong absorption of AEP (and a dynamic electrical energy E_{ein} as well, calculated as the area of the surface above the line near B: $E_{ein} = 9.78\ Wh$) from 220 W (the converter consumption) until the moment B when the spindle acceleration ceased and the steady-state running regime on 10,000 rpm starts. This electrical energy E_{ein} is converted and stored as mechanical kinetic energy E_{mk}.

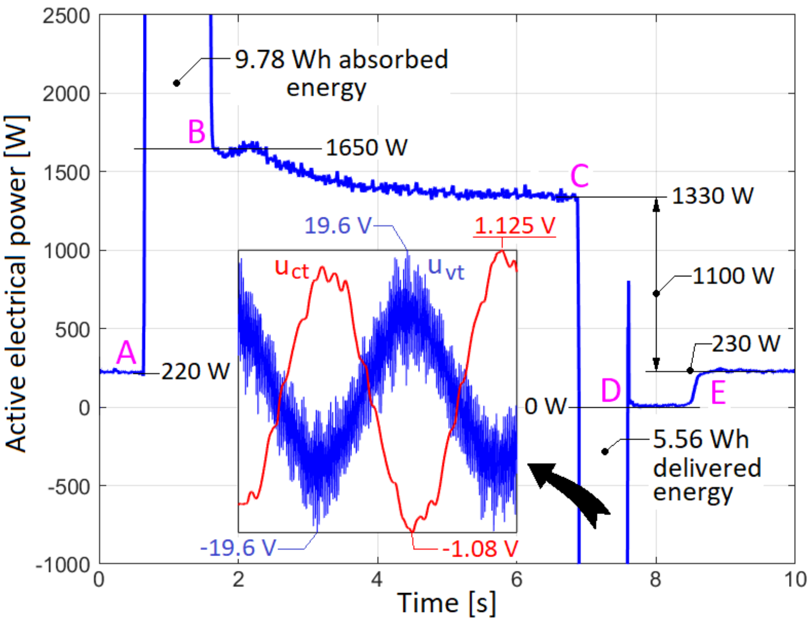

Fig. 9. A description of AEP evolution from Figure 8 in steady-state area

The relationship between E_{ein} and E_{mk} is evidently described with the conversion efficiency $\eta_{e\text{-}m}$ (electrical to mechanical) as:

$$E_{mk} = \eta_{e-m} \cdot E_{ein}. \tag{7}$$

In B starts the steady-state regime. The motor spindle turns with constant speed, the AEP decreases slowly from 1650 W to 1330 W in C (due to the decreases of internal friction forces). Between B and C the AEP delivered covers mainly the internal friction of spindle motor. In C the spindle motor is stopped by braking action of the AC/AC converter. This braking is done with a shift of phase of π radians between average voltage and current (revealed on Figure 9 with the relationship between u_{ct} and u_{vt}) with a strong negative AEP up to the moment D. This negative AEP means that an electrical energy E_{eout} (calculated as the area of a surface below the line near D as: E_{eout} = 5.56 Wh) is delivered to the electrical network. Now the spindle motor converts the mechanical kinetic energy E_{mk} (previously stored) in electrical energy E_{eout} with a conversion efficiency η_{m-e} (mechanical to electrical), described by:

$$E_{eout} = \eta_{m-e} \cdot E_{mk} \tag{8}$$

With a good approximation we can assume that $\eta_{e-m} = \eta_{m-e} = \eta$. Based on Eq. (7) and (8) and the results from Figure 9 this efficiency η results as:

$$\eta = \sqrt{\frac{E_{eout}}{E_{ein}}} \tag{9}$$

With the results from Figure 9 (E_{ein} = 9.78 Wh and E_{eout} = 5.56 Wh) and Eq. (9) this efficiency is calculated as η = 0.753. It is defined as $\eta = \eta_c \cdot \eta_{sm}$, with η_c being the efficiency of the AC/AC converter and η_{sm} the efficiency of spindle motor. If we assume that η is constant, this efficiency helps to calculate the mechanical power ($N = M_t \cdot \omega$, the torque M_t multiplied by instantaneous angular speed ω) delivered by spindle motor during a cutting process based on AEP variation ΔP generated by this process as:

$$N = \eta \cdot \Delta P \tag{10}$$

or to calculate directly the torque M_t if ω is known:

$$M_t = \frac{\eta \cdot \Delta P}{\omega} \tag{11}$$

It is important to highlight that a low value of efficiency (worst for energy consumption) has a positive effect when a mechanical load is mirrored in AEP evolution because $\Delta P = N/\eta$ (from Eq. (10)) or $\Delta P = M_t \cdot \omega/\eta$ (from Eq. (11)). Here $1/\eta$ (with $\eta < 1$) acts as an amplification factor.

All the consideration related by this experimental calculus method of efficiency η completed in Eq. (9) are true only if no other supplementary braking systems (mechanical or electrical) are used to stop the spindle motor between C and D moments. Otherwise the Eq. (8) is wrong: $E_{eout} < \eta_{m-e} \cdot E_{mk}$.

On Figure 9 a total amount of 1100 W AEP is necessary only to rotate the spindle motor in steady-state regime (no external loading). Between the moments D and E the AEP is zero, probably now the converter is electrically supplied by the electrical energy delivered by spindle motor, or the converter is completely stopped in order to avoid the rotation of the spindle motor in opposite direction (the braking between C and D means to supply temporarily the motor to rotate in opposite direction). That is why the voltages u_{vt} and u_{ct} shown in the detail from Figure 9 (or the voltage and current applied to spindle motor as well) are out of phase.

5. Conclusions

Some experimental achievements on computer assisted AEP spindle motor monitoring on a CNC machining center during a transient regime were revealed. An appropriate experimental setup, theoretical approach and signal processing procedures to describe the dynamics of this regime were proposed, with some relevant experimental results (e.g. the estimation of conversion efficiency η from electrical energy/power to mechanical energy/power).

There are many resources to exploit in a future research. Firstly an improvement of the experimental setup with information related by speed and acceleration during transient regimes is necessary (using sensors of spindle motor angular position or speed) in order to describe exactly the evolution of dynamic torque.

Many other transient and steady state regimes require a careful attention (e.g. the start/stop cycle of feed drive system motors). Also an interesting topic is related with cutting processes and tools condition monitoring and diagnosing (using the AEP and IEP evolutions in time and frequency domains), the spindle motor being used as a natural loading sensor (based on Eq. (11)) avoiding the utilisation of any measurement components (e.g. sensors) placed in working area. Some privileged directions of research will be: the study of the torque and the mechanical energy dependence by tool type and size or cutting regime parameters, tools mechanical loading optimisation in cutting processes, improving the cutting processes dynamics (avoiding the self-excited vibrations), etc.

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