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POWER PULSATION IN CONVERTER TRACTION DRIVES

Grzegorz Skarpetowski (1), Adam Szeląg(2)
Cracow University of Technology(1), Warsaw University of Technology(2), Poland

Abstract
The article presents instantaneous power flow through the selected elements of widely known DC-AC and AC-AC drive systems. The classic DC-DC drive system with a serial machine and a resistance starter is used as a comparative system. The presented values include: instantaneous value of power consumed from a network, instantaneous powers at inputs and outputs used in a static converter drive, power consumed by a traction machine and its developed torque. Power pulsation transfers up to the mechanical part of the system. Power pulsation is not directly visible, so the use of measuring devices is required, while mechanical pulsation not only causes damage to the elements in mechanical sub-assemblies of a system, but also can cause discomfort to the passengers of a vehicle. Considering the unavoidable power pulsation, while designing the whole system, would significantly increase the reliability of these modern and energy-saving drive systems.

Introduction

The last two decades have been marked by rapid development of converter traction drive. It stems from the fast growth of semiconducting elements as well as advanced progress in the technology of electric valves, miniaturisation and digitisation of control systems and progress in interference-free transfer of information. Under energy savings slogan, one might uncover undeniable progress in almost all areas of life. It applies to electric drive systems as well. Power electronics is with no doubt a drive force of the observed progress, however it seems like some aspects have been forgotten and insufficient actions have been undertaken, which resulted in serious negligence as fast as modernisation and adjustment of mechanical part elements are concerned. Increased reliability of the electrical part also highlighted the real size of the issues related to the mechanical part of traction drive systems.

Power balance in a vehicle's drive system

In the motion of a traction vehicle, the following phases of a ride can be distinguished [3,12]:

- start-up with 2 phases. In the first phase – constant starting force $F = Fmax$: (Fig. 1) [3], – acceleration $a > 0$ is of the highest level, $j = da/dt$ - jerk appears, at first positive, then negative, speed increases in a continuous manner, P mechanical power that is developed on the wheels increases as well,
- starting with transition to the phase 2 – of constant power P occurs when a traction force F begins to decrease, a acceleration also decreases, while v speed still increases (but slower) to the point of speed of set ride – maximum,
- ride at a set speed ($F = W,\ a = 0,\ P = const$), the largest increase in route occurs (3 – Fig. 1),
- coasting ($F = 0,\ a < 0,\ P = 0$) (4 -phase Fig. 1),
- braking ($a < 0$, $F = F_h < 0$, $P = P_h < 0$) (5th phase - Fig. 1).

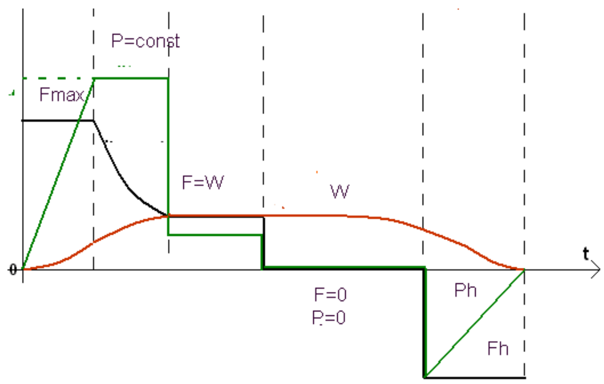


Fig. 1 Phase of a traction vehicle ride [3]

In conditions of mains supply, electric power consumed from a catenary depends not only on the vehicle's running phase, but also on voltage in a catenary (Fig. 2). It is therefore important that $_m$ power conversion in a vehicle is controlled in such a manner, so as to adjust the output mechanical power on the wheels $-P_m$ to the requirements regarding motion with alternating voltage at pantograph U_p (Fig. 2). Control possibilities depend on the type of a drive used in a vehicle.

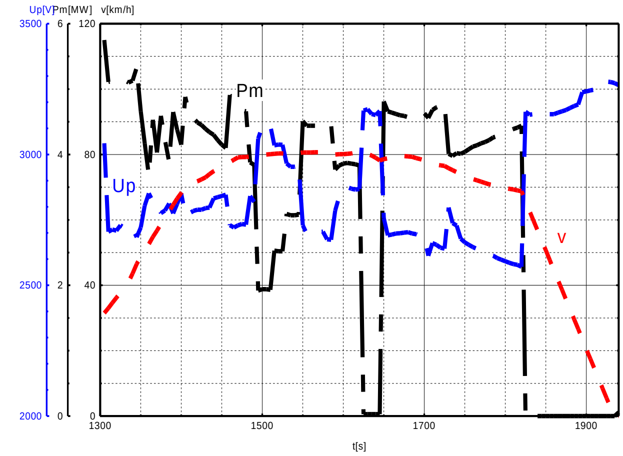


Fig. 2 An exemplary run of an electric vehicle supplied by a 3 kV DC system (v-speed, U_p-voltage at its pantograph, P_m- mechanical power versus time)

Classic DC-DC drive system

The simplest, traction drive system supplied from a constant voltage network (rectified voltage) and equipped with a series DC machine with resistance starter is presented in Figure 3.

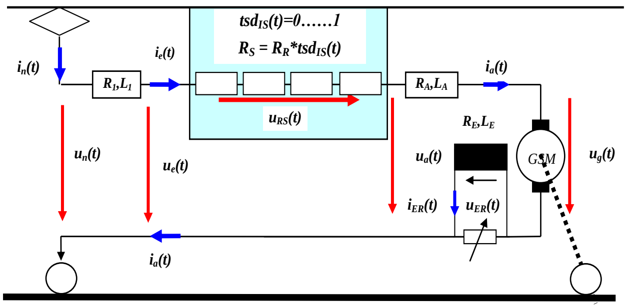


Fig. 3. Classic DC-DC drive system with a resistance starter

It is one of the best as well as most reliable drive system with extremely simple construction of mechanical parts. This drive has become widely used in the countries with a DC supply system. The drive is presented as a comparison system due to the particularly smooth transfer of power through the whole drive system.

Power flow through a classic drive system with a series AC machine is shown in Fig. 4. Power consumed from a network by a drive system presented in Fig. 3, power flowing to the series machine, hence power at the machine's shaft is constant in steady states and less variable in quasi-stationary, dynamic states. Only when the value of resistance connected to an armature circuit is changed or the value of shunting resistance, an excitation winding achieves a step dynamic state.

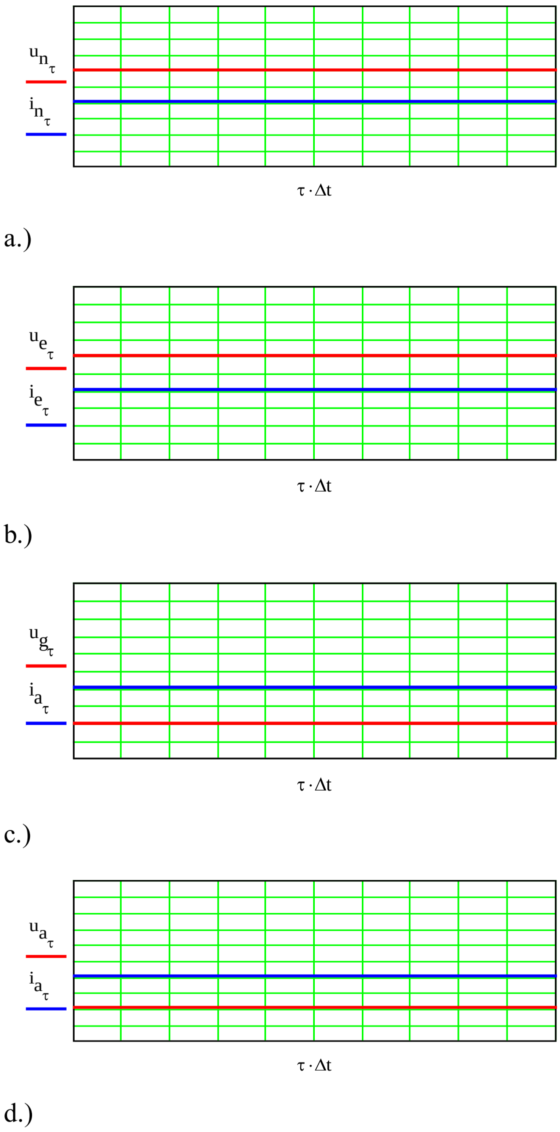


Fig. 4 Waveform of instantaneous values of power coordinates in a classic DC-DC drive system. a) power consumed from a network, b) 3 starter, d) power at the machine's terminals.

However, such waveform is not a very common one. Its influence on the mechanical part of a drive system is reduced to some extent using nose suspension of a motor. In dynamic states, single torque imposed is stored in nose-suspension springs and returned to the system after the termination of the dynamic state. In this classic drive system supplied from a well-filtered substation, there is no considerable, periodical power pulsations in the armature's current that transfer up to the transmission gear of the system. Influence of non-attenuated harmonics of substation voltage as well as voltage harmonics generated by a commutator on power flow through sub-assemblies of a drive system are negligible. They influence traffic control and signalisation systems only.

Converter traction drive with a series DC machines is presented in Fig. 5.

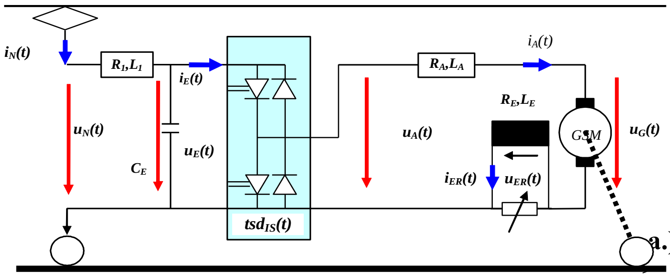
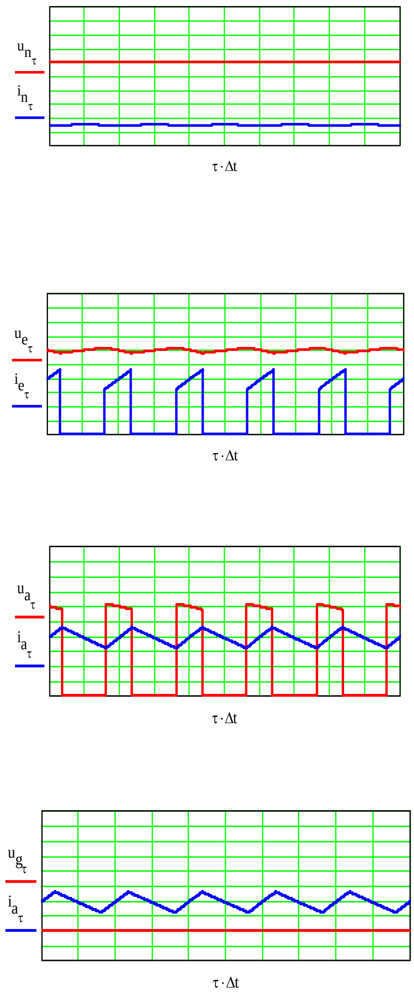


Fig. 5 Converter DC-DC drive system. Impulse controller with all necessary passive elements is introduced in place of a resistance controller. Voltage circuit is required at the input and current circuit at the output.



a.) b.) c.) d.)

Fig. 6 Waveform of instantaneous values of power coordinates in a converter DC-DC drive system

Power harmonics in a converter drive of DC-DC type

Pulse controller supplies a DC machine with power that is required at a given system operation point and consumes only this value from a supply network.

In a converter DC-DC drive system an uneven flow of power through system's sub-assemblies is observed. Power at converter's input is the power of a voltage circuit. Voltage has a value equal to the value of network voltage, and power is regulated by the current change in this circuit. Current consumed by a converter pulses in step of the change of conductivity of a pulse controller between a zero value and a value equal to current at the output. Output circuit is a current circuit. Average value of current in this circuit depends on demand for torque. Pulsing voltage occurring at the converter's output has average value depending on angular velocity of a machine's rotor. Power consumed by a system from a network is smoothed by an input filter that is necessary in this system, and this power consists of harmonics resulting from switching frequency of a pulse controller [1,2] (Fig. 6a), power consumed by a converter pulses as a result of pulse consumption of current from input circuit; stepwise changeable current is not consumed directly from a network, but from a capacitor, i.e. input energy storage that is constantly being charged with DC current from a network (Fig. 6b) output power of a converter, inside which there is no elements that store energy, and losses in a converter are implicitly omitted, has the same instantaneous waveform as input power, but with completely different values of power coordinates (Fig. 6c), power consumed by a traction motor does not pulse so hard as converter's output power, it is due to energy storage in the form of a choke smoothing current pulsations (Fig. 6d).

Power pulsation in a converter drive system of DC-AC type

Drive system of DC-AC is schematically represented in Fig. 7. This system is a typical representative of drive systems with inductive machine converter supplied with two-stage energy conversion [4,5,6,7,8,9,10,11,12]. First converter consumes energy from a network with widely changeable values of voltage [13,14] and supplies a DC intermediate circuit, in which a constant average value of DC voltage is maintained. 3-phase converter supplying an asynchronous machine consumes energy from this constant voltage intermediate circuit.

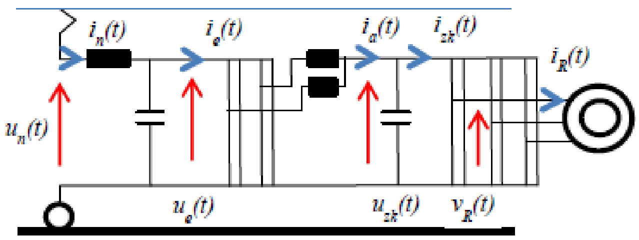


Fig. 7 Schematic diagram of a simple DC-AC converter drive system with double energy conversion

The operation of an input filter of the first converter is similar to the one described in a DC-DC system. Instantaneous power flow inside the converter drive system of DC-AC type is shown in Fig. 8. Fig. 8a shows power consumed from a network presented by means of its coordinates (u,i). Apart from a current waveform, output voltage waveform of supplying station rectifiers that is close to real values is shown as well. Fig. 8b shows instantaneous power stored in a capacitor of an input filter. It is a difference between power consumed from a network and power given to the network converter's input. Fig. 8c shows two-channel power supply through pulse controllers of a network converter. Total power reaching to an intermediate circuit from network side is shown in Fig. 8d. Fig. 8e shows the difference between power supplied by a network converter and consumed by a 3-phase traction converter. Fig. 8f shows power consumption from an intermediate circuit by a traction converter. What is visible is the important role of an intermediate circuit capacitor in smoothing of power flow between both converters of a drive system. Fig. 8g shows instantaneous power value consumed by one phase of an asynchronous machine, which is converter supplied in the range of control – the so-called range of weakened field with one-block pulsation. Instantaneous power value at machine's shaft is shown by means of torque, i.e. coordinate of mechanical force power in Fig. 8h. Speed coordinate of this power has an assumed constant value.

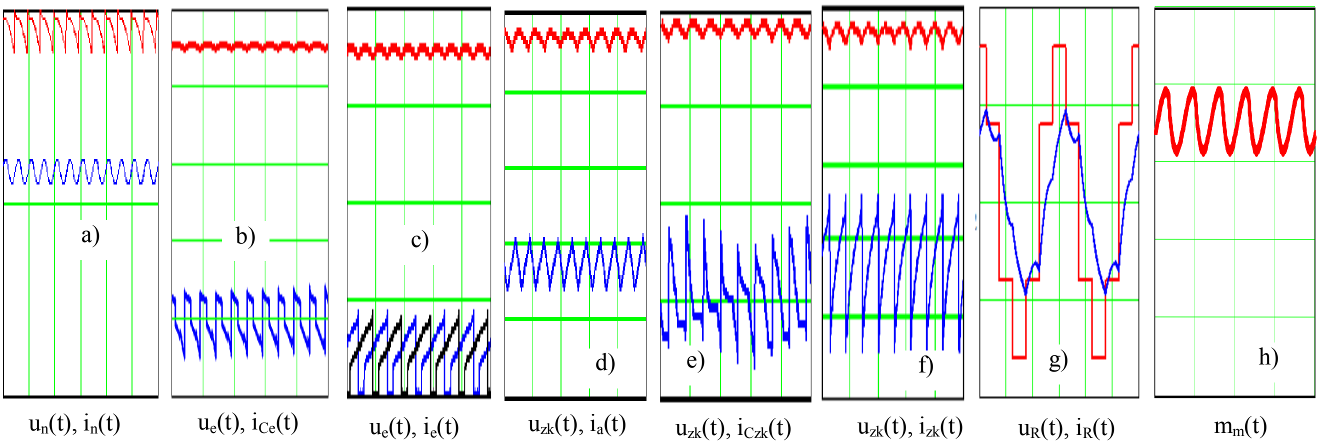


Fig. 8. Instantaneous value of power coordinates (voltage and current) in a traction drive system of DC-AC type with double energy conversion

Power pulsation in a converter drive of AC-AC type

Diagram of a DC-AC drive system is presented in Fig. 9. It is a typical traction drive system well known from the literature. All converters of this system operate in a pulse mode. It can be used for all AC traction networks.

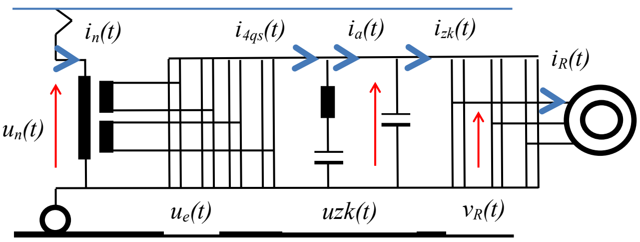


Fig 9. Schematic diagram of a converter drive system with an asynchronous machine supplied from an AC network

While its universality consists in the possibility, even after small changes, of adjusting to the cooperation with DC networks. This system is equipped in a special filter smoothing power consumption from a catenary. Single-phase supply results in power consumed from a network pulsing with double network frequency.

The waveform of power pulsation depends only on a phase shift between voltage and current. With cos(fi) =1, power consumed from a network is an active power only.

Fig. 10a shows a waveform of AC network voltage (red) and network current (blue). Current is in phase with voltage.

The product of these values is still positive, but it has double frequency. Network current is the result of adding up the flow in a transformer's core.

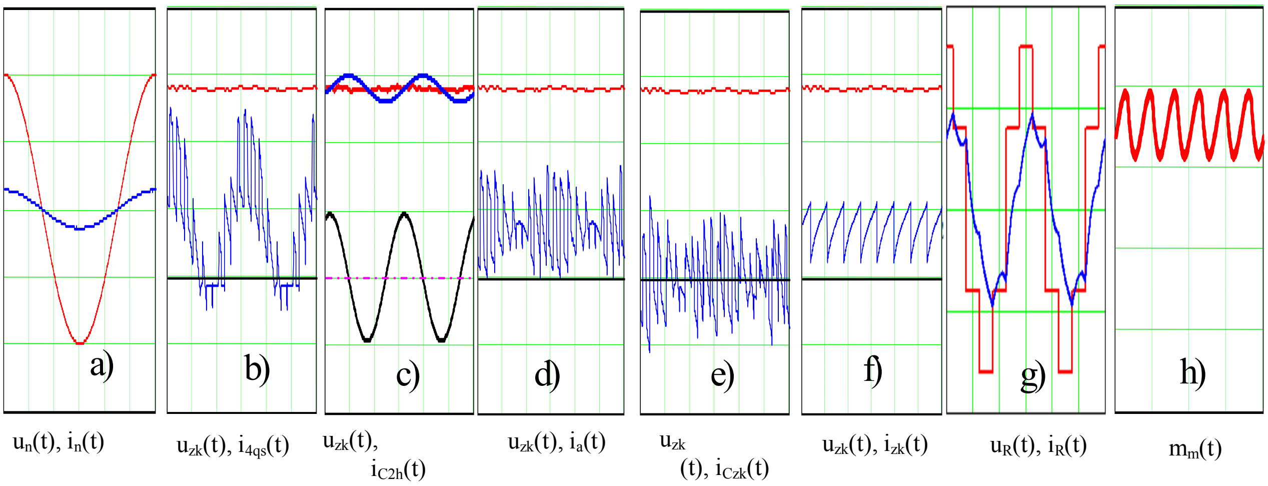


Fig. 10. Instantaneous value of power coordinates in a traction drive system of AC-AC type.

Instantaneous power at four-quadrant converter's output is shown in Fig. 10b. At converter's output, there is voltage with constant average value. Its output current is pulse adjusted, shifted by its average value with a waveform with sinusoid envelope and doubled frequency (in comparison with the network). If this pulsing power was carried to traction motors, then it would not be possible to tall about comfort as far as rail communication is concerned. Therefore, at four-quadrant converter's output there is a filter attached, in the form of a series resonance circuit (Fig. 10c), which fulfils the role of an electric flywheel. This filter reacts with double frequency to surpluses and deficits of power consumed from a network. When power from network is higher than the average value, this filter stores energy, and when the network does not cover demand for active power, the filter returns the stored energy. What can be observed is considerable current flowing through this significant filtering circuit. Fig. 10d presents power from quarter-quadrant converter with a filtering circuit attached. This power is driven to the intermediate circuit that maintains a constant average value of voltage $u_{zk}(t)$. Power consumed from an intermediate circuit and carried to the input of a 3-phase converter is shown in Fig. 10 f. What can be observed is the difference between instantaneous values of power flowing into and out of this circuit. The difference is covered from energy resources stored in a capacitor of an intermediate circuit, and instantaneous power consumed from this circuit is shown in Fig. 10e. Powers presented in Fig. 10g and Fig. 10h were already discussed in a previous drive system.

Conclusions

- Supply networks of “constant voltage” allow for consumption of almost constant power, however they introduce harmonics into drive systems, and the influence of these harmonics can be intensified in converter systems as a result of their entanglement with harmonics of converter switching frequencies. (influence in signalling) [1.2.7.10]
- AC supply networks are loaded with almost constant power, but only with supply by 3-phase sinusoidal voltage. Single-phase networks supply only pulsing power with double network frequency. Pulsation of power consumed from a network with constant frequencies (2*16.7 Hz and 2*50 Hz and 2*60 Hz) can be relatively easy, but with large effort, compensated using a series resonance filter tuned precisely to double frequency of this network. This filter stores energy surplus that comes from a network in a half-period of power higher than the average value and it returns the energy immediately to the receiver in a half-period of deficit of power supplied by a network. The filter can be used in drive systems of AC-AC type.
- Very often, AC networks do not fulfil the condition of sinusoidal voltage and are the source of considerable amount of voltage harmonics as well as additional power pulsation.
- Power supplied by the AC network is limited by total impedance of the network and impedance of transformers that occur on a path to point of common coupling.
- Converter systems transfer energy in a pulse manner
- Each power conversion introduces new frequency harmonics and generates new entanglements.
- All energy converters generate in electrical machines pulsations of mechanical power.
- Amplitudes of these pulsations do not depend on load state of a machine, and are the same for the states of ride, idle state and braking. Only no-current idle state is void of these pulsations.

- Amplitudes and frequencies of these pulsations depend on manner of converter operation control.
- Power pulsations in electrical part can be reduced only in a very limited range.
- Power pulsations are transferred to the mechanical part of a drive and cause additional dynamic load for a transmission gear, decoupling parts and traction machines as well.
- Pulsations are the cause of fast ageing of and damage to electro-mechanical elements of a power transfer system in converter traction drive systems.
- When the power is transferred from the motor's shaft to the vehicle's axle, there must occur power pulsation smoothing, and high frequency storage of the energy surplus in elastic elements being capable of returning this energy under conditions of energy deficiency.
- This task cannot be fulfilled in converter drive systems only by means of nose-suspension, and it is due to the too low frequency of potential reaction.
- Nor is it fulfilled by a rubber coupling since rubber spacers can deform permanently very quickly.
- However, this objective can be met only by elastic elements with high durability that are capable of storing considerable amount of energy and reacting very fast to the change of power being transferred.

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