

Currents' Physical Components (CPC): a new framework for studies on Power Quality and its improvement and some observations

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Abstract. The article shows that the term “Power Quality” (PQ) seems to be only engineering jargon, therefore, it is suggested that the terms “Supply Quality” (SQ) and “Loading Quality” (LQ) are used in studies on Power Quality in electrical systems. Studies on PQ are associated with studies on Power Theory (PT) and compensation in systems with nonsinusoidal voltages and currents. Unfortunately, there is more than century-long confusion on powers in electrical systems and several mutually conflicted schools of PT have occurred. The only yet not challenged concept of PT is that based on the Currents' Physical Components (CPC), developed by the author of this article. Therefore, it seems that just CPC-based PT should be used as a fundamental for studies on PQ. The paper presents a short draft of the CPC concept with an emphasis on the physical interpretation of energy flow-related phenomena. Some observations related to renewable energies, and global warming, are included as well.

Key words. Power Theory, switching compensators, hydrogen cars, wind farms, global warming.

1. Introduction

The author of this keynote is not involved in studies on Power Quality or Renewable Energies. He has only some expertise in studies on energy flow phenomena in the presence of voltage and current distortion, on the physical interpretation of these phenomena, and the definitions of electrical powers. He has also some expertise in methods of compensation in electrical systems.

Studies on Power Quality and Renewable Energies are outside of this area, so the author is not competent in these subjects. They are mutually associated, however, and therefore the author has some external perspective on Power Quality and Renewable Energies issues.

2. The Term “Power Quality”

Scientists and engineers involved in Power Quality (PQ) issues probably do not have problems with the term “Power Quality”, but people from outside of the PQ area can ask questions: **What is it? How is it defined?**

The PQ issues are a part of electrical engineering, which is founded on physics. In a physical sense, “power” does not have quality, however. Thus, the term “Power Quality” looks only like a piece of engineering jargon.

This has some consequences. There are a lot of devices called “PQ meters” on the market. They measure or record harmonics, noise, dips, asymmetry, distortion, or the RMS variation of voltages and/or currents at power system points where they are connected. Do they measure Power Quality? No, they measure specific phenomena for which they were designed but not PQ. Even more. Let us suppose that a PQ meter, connected at load terminals, measured a harmonic distortion of the load current. This distortion can be caused by the load, the supply system, or both. The PQ meter does not provide information on what is the cause of this distortion. Similarly, a PQ meter has measured the voltage asymmetry at the load. Again, it can be caused by the load imbalance, by the supply, or by both. Disconnecting the load can help in identification, but disconnection could be not possible, however.

3. Loading Quality and Supply Quality

Unlike as it is with power, the concept of “a quality” can be associated with the properties of the supply source. The best, ideal, is the supply source of unlimited power that provides the load with a sinusoidal and symmetrical voltage of a constant

RMS value. Any divergence from such an ideal supply source by harmonics, noise, notches, pulses, asymmetry, or the supply voltage RMS value variation in time or the load change can degrade the load performance. Thus, we can talk about the supply in terms of quality, i.e., use the term “Supply Quality” (SQ).

The agents that cause a divergence of the source performance from the ideal one affect the load performance differently, so it is unlikely that the Supply Quality can be defined to endow it with a numerical value, however. The concept of “quality” can be also associated with the properties of electrical loads. The best, ideal load, is a load that at sinusoidal and symmetrical supply voltage has a sinusoidal symmetrical current that is in phase with the supply voltage. Any divergence from such a current, caused by the load properties, meaning the presence of distortion, noise, notches, pulses in the load current or its asymmetry can disturb the performance of the supply equipment. Thus, we can talk about the load in terms of quality, i.e., use the term “Loading Quality” (LQ).

Similarly to the Supply Quality, the agents that cause the divergence of the load performance from the ideal one affect the supply system differently, so it is unlikely that the Loading Quality can be defined to endow it with a numerical value.

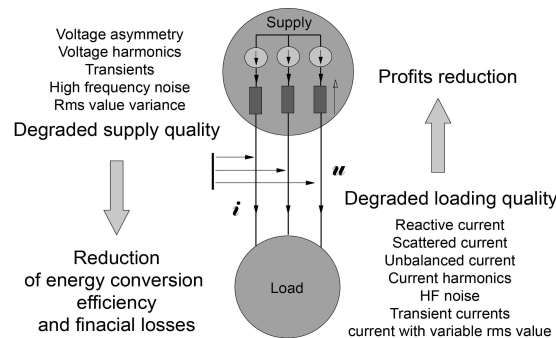


Fig. 1. Diagram of effects of degraded Supply Quality and Loading Quality.

4. Power Quality versus Power Theory

Though studies on PQ and PT refer to the same area of electrical engineering, meaning electric energy delivery, they have different perspectives and objectives. Selection of power definitions, physical interpretation of energy flow-related phenomena, and power factor improvement which are objectives of studies on PT, are not objectives of studies on PQ. Studies on PQ are rather focused on disturbances of the distribution systems and loads by various factors that degrade PQ, on its improvement, and on countermeasures that could prevent the system and loads from such disturbances.

Studies on PQ should follow some results obtained in studies on PT, however, at least those that are related to the explanation and physical interpretation of phenomena that occur in electrical systems at energy transfer. Some of them degrade the effectiveness of this transfer and the Power Quality.

Unfortunately, there is a century-long controversy on the power properties of electrical systems, which started with Steinmetz’s observation in 1892 [1] that the power equation

$$S^2 = P^2 + Q^2 \quad (1)$$

is not valid in circuits with nonlinear loads. In response to this observation, several schools of PT, that explain the power-related phenomena in mutually different ways, were established. These schools are presented and discussed in detail in [2]. They were disseminated in the EE community through articles, books, as well as by national and international standards. They affected all research on systems with nonsinusoidal currents, including, of course, research on Power Quality. Unfortunately, major misinterpretations were identified in these schools of PT, compiled in [2], both as to the physical interpretation of the energy flow-related phenomena and methods of compensation.

5. Currents’ Physical Components Concept

The concept of Currents’ Physical Components (CPC), developed by the author of this article; has as its fundamental the identification of physical phenomena associated with energy flow in electrical circuits and the question of how they affect the effectiveness of energy transfer in such circuits. It clarifies the century-long controversies as to power-related phenomena in such circuits and methods of power factor improvement, meaning compensation.

The CPC concept applies to single-phase and three-phase circuits. In its most advanced form, it applies to three-phase circuits with a neutral conductor of the structure shown in Fig.2.

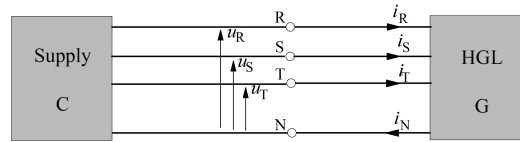


Fig. 2. A three-phase circuit with neutral

The supply voltage can be nonsinusoidal and asymmetrical. It can be expressed in terms of harmonics u_n of the order n from a set N as follows:

$$u = \begin{bmatrix} u_R \\ u_S \\ u_T \end{bmatrix} = \sum_{n \in N} u_n = \sqrt{2} \operatorname{Re} \sum_{n \in N} \begin{bmatrix} U_{Rn} \\ U_{Sn} \\ U_{Tn} \end{bmatrix} e^{jn\omega_1 t} \quad (2)$$

The load can be linear or a Harmonics Generating Load (HGL). The load can be a source of current harmonics because of nonlinearity or periodically changed parameters, as it is power electronics devices. It draws the current which is the sum of harmonics i_n , namely

$$i = \begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix} = \sum_{n \in N} i_n = \sqrt{2} \operatorname{Re} \sum_{n \in N} \begin{bmatrix} I_{Rn} \\ I_{Sn} \\ I_{Tn} \end{bmatrix} e^{jn\omega_1 t} \quad (3)$$

The load current can be decomposed into seven components, namely

$$i = i_{aC} + i_{sC} + i_{rC} + i_{u0}^z + i_{u0}^p + i_{u0}^n + i_G \quad (4)$$

which are associated with seven distinctive, energy flow-related phenomena in the circuit. These are:

- i_{aC} – **active current**, the only current component associated with useful energy transfer to the load.
- i_{sC} – **scattered current**, a useless current component associated with the phenomenon of the load conductance change with harmonic order.
- i_{rC} – **reactive current**, a useless current component associated with the phenomenon of the phase shift of the voltage and current harmonics.
- i_{u0}^z – **unbalanced current of zero sequence**, a useless current component associated with the presence of the zero sequence harmonics in the supply voltage.
- i_{u0}^p – **unbalanced current of positive sequence**, a useless current component associated with the presence of the positive sequence harmonics
- i_{u0}^n – **unbalanced current of negative sequence**, a useless current component associated with the presence of the negative sequence harmonics
- i_G – **generated current**, a useful current component associated with the generation of current harmonics in the load which transfer energy from the load back to the supply source.

Because of the association of these current components with physical phenomena in the circuit, they are referred to as “Currents’ Physical Components”. Apart from the active current, i_{aC} , all of them contribute to the reduction of the effectiveness of energy transfer to the load, thus to the degradation of the power factor. They could be reduced or eliminated by compensators. The kind of a compensator, its structure, properties, and control depend on which of the six current physical components is to be compensated.

6. Reduction of Load Current Harmonics

The most common in studies on Power Quality and Power Theory are those on technical tools that can improve the power factor and can improve the PQ, meaning studies on filters. Studies on methods of reduction of harmonic distortion are one of the most important practical implementations of the power theory. Their conclusions can be useful also for studies on PQ improvement by reducing currents’ harmonics.

One of the most commonly used devices for reducing currents’ harmonics is the voltage source inverters of the basic structure shown in Fig. 3.

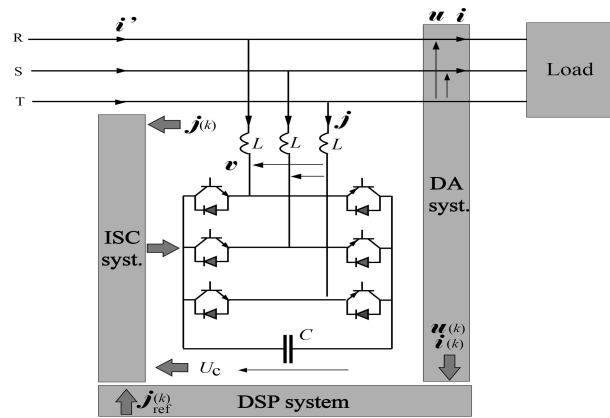


Fig. 3. Voltage source inverter structure with control subsystems.

They are equipped with data acquisition (DA), Digital Signal Processing (DSP), and an Inverter Switch Control (SC) systems.

Such devices are usually called “active harmonic filters”. This name is misleading, however. They consume energy, thus they are not active but passive devices. They can reduce not only current harmonics but also the reactive current, current asymmetry, and transients. Thus, the adjective “harmonic” is not appropriate. Moreover, they do not operate as filters but as compensators. Therefore, a new name was introduced for such devices, namely, “switching compensators”.

Such a compensator can compensate any of the CPC as listed above, but for enhancing the power ratings of the compensator, the reactive and unbalanced currents can be compensated by reactance compensators in a hybrid structure [2]. The switching compensator is mainly used for reducing current harmonics.

Compensation in the frame of CPC can be performed by reactance compensators, by switching compensators, and by hybrid ones, composed of reactance and switching ones [...]. It enables adjusting the compensating tools to the situation and enhances the compensator’s capabilities.

When a load generates current harmonics, as it is usually with loads with power electronics devices switching compensators are needed. An example of such a load with a hybrid compensator is shown in Fig. 4.

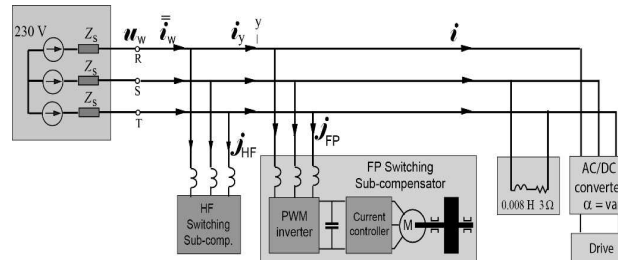


Fig. 4. An example of a circuit with a (HGL) and variable active power with a hybrid compensator

Waveforms of voltages and currents of the load and the active power P variation with the change of the firing angle of the AC/DC converter are shown in Fig. 5.

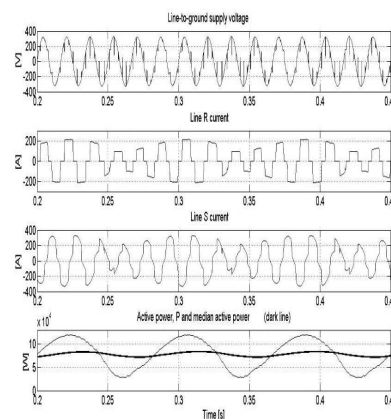


Fig. 5. Waveforms of the load current in lines R and S, the supply voltage and the load active power P .

Observe, that due to current commutation by the AC/DC converter, deep commutation notches are visible in the supply voltage. Changes in the firing angle of the AC/DC converter cause variations of the load active power P . Therefore, to compensate the active load variability, a large storage of energy was needed in the considered circuit. A flywheel which was driven by an induction machine was used for that purpose. The compensator was designed as a hybrid compensator composed of a high-frequency sub-compensator (HF) of the load current, a low-frequency sub-compensator for compensating variation of the active power P , and the reactive current of the fundamental frequency. The results of compensation are shown in Fig. 6.

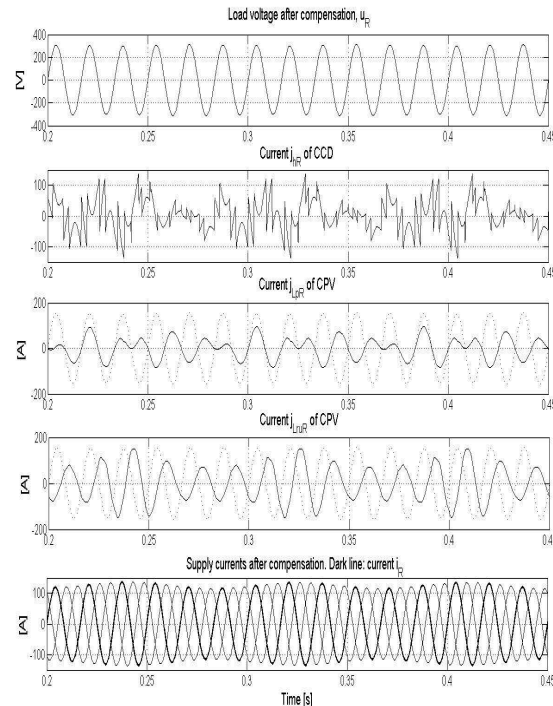


Fig. 6. Results of compensation

This illustration demonstrates the potential of the CPC concept for handling compensation in electrical circuits. The author of this keynote is not, however, expert on Power Quality. Therefore, he cannot tell which elements of that concept could contribute to studies on the PQ. He strongly believes, however, that CPC clarifies the phenomena in electrical circuits associated with energy transfer and this clarification could be beneficial also for studies on PQ. Power terms are used in these studies. Also, comprehension of the properties of electrical circuits seems to be important for it. These terms and the comprehension based on the old schools of the Power Theory could be incorrect, however. Only the CPC-based PT was not yet challenged as erroneous.

7. Observations on Related Issues

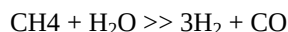
The conference covers a very broad range of subjects, from Power Quality to renewable energies sources. These sources are not the area of expertise of the author of this keynote. Nonetheless, the studies on the Power Theory, somewhere between, were carried on by the author in the shadow of a huge debate and investigations on environmental issues, global warming, carbon dioxide emission, and renewable energy sources. Therefore, it was not possible to avoid some observations on that debate.

By studies on compensation, meaning methods of energy savings, the author contributed a bit to these investigations, but he is essentially an ignorant on the majority of the investigated and debated issues. Maybe therefore some conclusions from this debate can a bit astonish and raise questions. Some of them are shown below.

Conclusions from Fukushima disaster. After the Fukushima disaster, experts on nuclear plants in Germany concluded that all nuclear plants in Germany should be closed. At the same time, the president of the United States, Obama, announced that according to his experts on nuclear plants, such plants are the safest, produce the cheapest energy, and disturb the environment to the lowest degree. Therefore, the States will embark on the program of building thirty new nuclear plants. Thus, the question can be asked: *Where does this major difference in opinions between experts on nuclear plants in Germany and the States come from?*

Ideally green” hydrogen cars, according to very common opinions, hydrogen cars can substantially contribute to slowing down global warming. This opinion was supported by the California Energy Commission (CEC) by supporting [3] “the adaptation of zero-emission hydrogen fuel cell electric cars”, by expanding California’s network of hydrogen refueling stations, with the goal to get 1.5 million zero-emission vehicles in California by 2025.

Hydrogen fuel cells are zero-emission devices but what with hydrogen they need? According to Wikipedia, 98% of hydrogen production in 2021 was from the process of steam reforming, methane, natural gas, or coal. Most of it is from methane (CH₄) reforming. Namely, at a temperature about 1000°C, the mixture of methane and water converts to hydrogen and carbon oxide



Next, at a temperature of approximately 360°C, this mixture with water converts to hydrogen and carbon dioxide



It means that from one kmol of methane of the mass:

$$m_{\text{CH}_4} = 12 + 4 \times 1 = 18 \text{ kg},$$

hydrogen of the mass:

$$m_{\text{H}} = 4 \times 2 = 8 \text{ kg}$$

is produced, along with carbon dioxide of the mass:

$$m_{\text{CO}_2} = 12 + 2 \times 16 = 44 \text{ kg}.$$

Thus, the question can be asked, **how these hydrogen cars were sold to customers as ideally green cars?** Even worse, when they were bought, due to the cost of hydro-gen production and distribution, the cost of hydrogen cars exploitation, according to [4], was 14 times higher than the cost of exploitation of common electrical cars.

Wind farms versus nuclear plants. I have at university a few coworkers and students very enthusiastic about the production of electric energy by wind farms. Some of them have even an opinion that instead of nuclear plants, wind farms should rather be developed.

A few kilometers apart from Louisiana State University, (LSU), there is a River Bend Nuclear Plant, with a 1500 MW generator. We can use this plant in a virtual experiment of replacing it with an equivalent to the power wind farm. Let us suppose that 3MW generators are used for that, so 500 windmills are needed for that. According to Prof. Lubośny [6] of Gdansk University of Technology, who measured the power annual variation of windfarms in Poland, shown in Fig. 7 (light blue), their effectiveness.

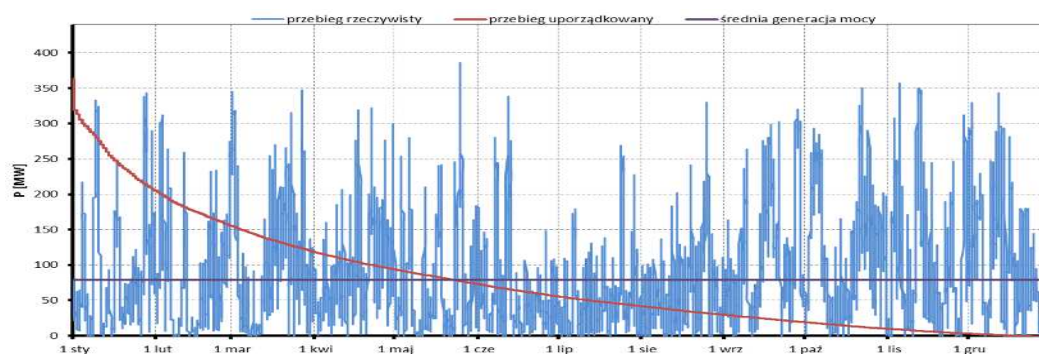


Fig. 7. Annual variation of power of all Polish windfarms with the installed power of 455 MW.

is only 18%. Thus, a wind farm with 2800 but not 500 windmills with 3 MW generators is needed for that. One could imagine how much the Earth's resources, such as land, aluminum, steel, copper, water, electric energy, natural gas, and workforce are needed for that. When we look at the plot of the arranged power of wind farms, (red line in Fig. 7), even if these resources are provided, the equivalent wind farm has the power of the River Bend plant only for five months. For the remaining seven months, it operates with lower power. Even worse, while nuclear plants are built to operate for 60-80 years, wind farms have a life expectation of the order of no more than 20-30 years. Thus, to be equivalent to a nuclear plant, the wind farm must be rebuilt 2-3 times. It means that, even if a substantial part of the needed materials could be reused, still several hundred thousand tons of pieces of debris, composed of concrete, aluminum, steel, copper, and plastic, must be a few times stored or utilized. The results of this virtual experiment provide me with an answer to the question: **should I share the enthusiasm of my colleagues and students on replacing nuclear plants with wind farms?** The answer is simple: no.

Earth – a Greenhouse? Even if various observations on climate-related phenomena are sometimes mutually conflicting, the grid of hundreds of thousands of temperature meters, located around the globe, sends a clear message: Earth goes over global warming.

In common opinion, the greenhouse phenomenon, caused mainly by carbon dioxide, is responsible for this warming. People's activity, mainly the industrial ones, is mainly blamed for CO₂ emission, and for global warming. The existence of the greenhouse phenomenon is scientifically confirmed, thus, the industry-related emission of carbon dioxide must contribute to global warming.

The question arises, however, whether only just this emission is the cause of global warming? In other words, if we imagine that somehow this industry-related emission be stopped, will this warming stop as well?

There are geological evidences that 130,000 years ago the Earth's climate went over an interglacial period. Europe was released from the ice cover. These geological evidences converges with the results of measurement of the Earth's temperature [5] in the last 400,000 years, shown in Fig. 8.

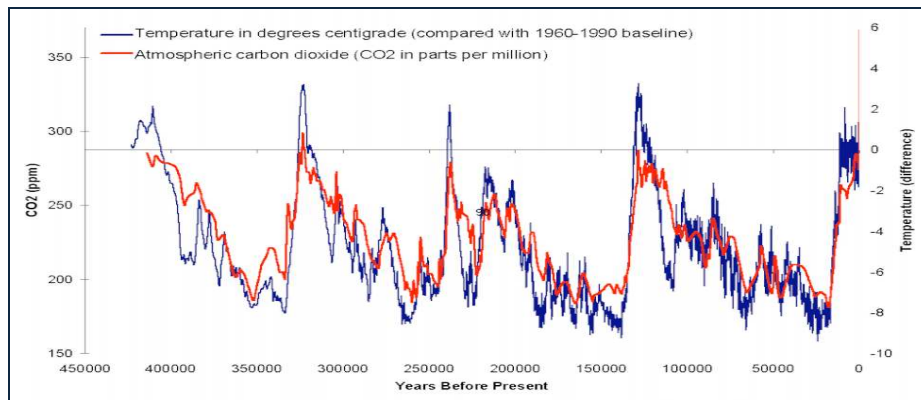


Fig. 8. The Earth's average temperature and atmospheric carbon dioxide.

These results show that in the last interglacial period, with the apogee approximately 125,000 years ago, with the global temperature 3°C above the present, the Earth's temperature increased by approximately 12°C . What was the source of the carbon dioxide in that interglacial period, if we keep the opinion that the Earth's warming was a result of the greenhouse phenomenon? For sure, it did not occur because of people's industrial activity. The present warming period, Holocene, started approximately 12,000 years ago. The main part of this global warming took place before the Egyptian pyramids were constructed, thus well before people's industrial activity. Thus, this activity can contribute to global warming, but other natural pheno-mena seem to be behind it as well. In particular, there could be direct changes in the Earth's warming, without the greenhouse phenomenon, caused by changes in the sun's radiation activity. Observe, for example, that at the end of the last interglacial period, the Earth's temperature fell by approximately 10°C , at almost constant atmospheric carbon dioxide, meaning, the greenhouse phenomenon did not work as expected. The same can be observed in other periods. Anyway, the time variations in the Earth's temperature and atmospheric quasi-periodic phenomenon, of the period between 100,000 and 130,000 years, which in the last half million resulted in global temperature changes in the range of approximately 11°C . The rate of temperature increase in the present Holocene period, also looks to be similar to that at the beginning of the last interglacial period and the previous ones. Thus, the following question can be asked: **what was the source of carbon dioxide in those times if we regard the Earth as a greenhouse?**

The NASA revelation. On February 7, 2019, the New York Times (NYT) reported that scientists from NASA concluded that according to their investigations, people's activity is responsible for global warming. This conclusion was drawn from measurements of global tem-perature shown at the front of the NYT and in Fig. 9.

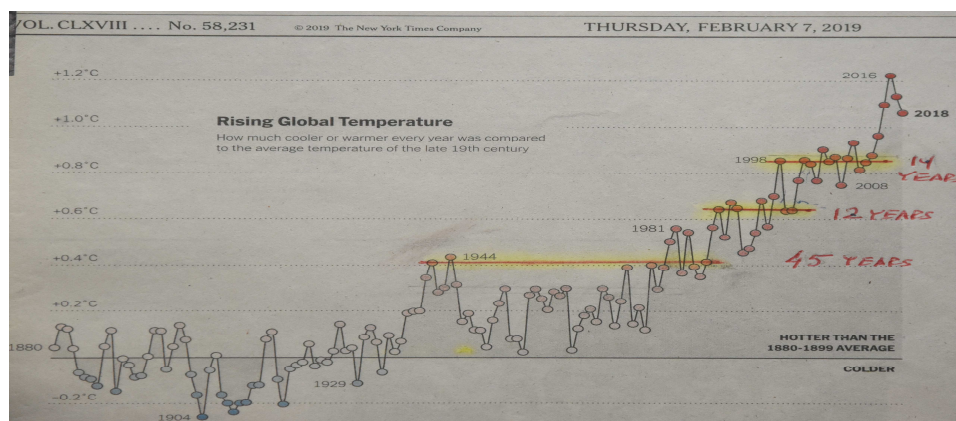


Fig. 9. Variation of the Earth's average temperature according to NASA

We know from the school's physics that any mecha-nical work converts to heat energy. Whatever we eat, on average 2500 kcal. a day; is released as heat to atmos-phase. Thus, NASA's scientists are right: we contribute to global warming, especially when people burn, moreover, natural gas, petroleum, coal, and wood, generate heat and produce carbon dioxide.

Looking at this diagram one can observe that between 1880 and 1936, thus over 36 years, the global temperature did not change. The Earth's population grew up at that period at the rate roughly of 0.9%, thus it increased approximately by 50%; electrical power systems with mainly coal and crude oil-driven power plants, and industrial emissions of carbon dioxide started. The effect of this activity is not observed, however, in this plot. Something happened after 1936 - in four years the global temperature jumped by roughly 0.3°C . After the next approximately 45 years, it did not change again. After the II World War, the Earth's population increased by roughly 7% a year, thus in 45 years increased almost three times. Adequately to this increase in population, also increased the people's industrial activity, thus carbon dioxide emissions. This is not visible in Fig. 9, however. After 1986, in five years, the global temperature jumped again by 0.2°C , but by the next 12 years, it did not change. This pattern was repeated after 1997, when in a few years the temperature jumped

by another 0.2°C , to stay unchanged for the next 14 years. The Earth people's activity does not change in a stair-like fashion, however. Thus, the following question can be asked: ***on what ground did the scientists from NASA conclude that the change in global temperature was caused by people's activity?***

8. Conclusions

These few observations justify a more general question: ***How our opinions are shaped, opinions that next result in major technological and economic decisions on the development of various energy sources?***

References

- [1] Ch.P. Steinmetz, "Is a phase-shift in the current of an electric arc?", (in German), *Elektrotechnische Zeitschrift*, Heft 42, 567-568, 1892.
- [2] L.S. Czarnecki, *Powers and Compensation in Circuits with Nonsinusoidal Current*, Oxford Univ. Press, 2024.
- [3] www.energy.ca.gov, California Energy Com. 2020.
- [4] www.hydrogeninsight.com, Hydrogen cars, 2023.
- [5] T.R. Klinert, "Greenhouse Phenomenon", Texas A&M Univ., The Climate Change Seminar, Antarctica, 2019.
- [6] Z. Lubośny, "Wind farms", Conf. on Automatic, Control and Disturbances, Jurata
- [7] , Poland, 2017.