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Analysis of the Use of Undervolting to Reduce Electricity Consumption and Environmental Impact of Computers

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1. General information

The point of undervolting is to reduce the voltage of the processor or graphics card without reducing their performance. This is possible because factory preset voltages are voltages set for low quality chips that require higher voltage to work properly. This way more manufactured processors can be used. It should be noted that current technology of manufacturing processors, even though they are very modern and are subject to numerous restrictions, do not guarantee that each processor will be the same high-quality sample. In case when the computer is equipped with a good quality processor, the voltage of the processor can be significantly lowered (Gizopoulos et al. 2019).

The analysis of the literature shows that undervolting is used nowadays to optimize the power consumption of complex FPGA (Salami et al. 2018, 2019) or processors (Koutsovasilis 2020). Undervolting not only brings with it the profit resulting from the optimal electrical energy consumption, but also contributes to lowering the temperature and noise of electronic devices and allows to change the frequency of digital circuits. The above-mentioned reasons are also applicable to modern WiFi sensors, which are dedicated to the circuits used in the Internet of Things applications (Kalau et al. 2014, Kalau et al. 2015). Undervolting is also a method of optimizing such unusual devices as crypto mining rigs (Oğuzhan et al. 2020).

Considering the analyzed literature on the subject, the presented work describes the significance of undervolting, presents practical ways of its implementation, and in particular shares the results of experiences that have not been previously presented in the literature in such an approach and scope. The detailed description and the range of experiences in which undervolting was approached as a method of electricity reduction in large computer infrastructure are presented in the following chapters of the paper.

The use of undervolting is very important because it reduces the problem of wasting electricity by electronic devices and the disposal of computer equipment. In the case of processors, excessive voltage affects the amount of heat generated by the processor. The result is high temperature of operation of both the processor and other computer components. This has a negative impact on the life span of components making them degrade faster. This requires frequent replacement of computer parts, the disposal of which is problematic.

The advantage of the undervolting is that it only requires a one-time configuration of the computer workstation by the administrator. This operation does not interfere with the use of other energy saving methods and may work alongside them. Undervolting works particularly well in combination with Intel AMT technology, as this technology allows for remote, real-time monitoring of the status of the computer (Muc et al. 2018, Intel, Tan et al. 2007). It is also worth noting that when the administrator uses the appropriate undervolting software, the configuration that reduces the processor's power consumption is automatically turned on when the computer is started (Hartung et al. 2019). No user involvement is therefore required. This is a very important, because the experience of the authors concerning other energy saving methods (Muc et al. 2018) shows that users are reluctant to follow the recommendations of the administrator or supervisor of computer equipment for the correct and ecological use of the workstations.

Undervolting of the processor consists in changing the voltage offset. This results in a voltage drop for all processor states (e.g. idle, load, heavy load). The voltage reduction results in lower power consumption, TDP (Thermal Design Power) and decreased noise (the cooling system operates more quietly because it dissipates less heat) (Kalau et al. 2014, Kalau et al. 2015). Processor manufacturers provide dedicated software for changing processor’s parameters, which, among other things, allows performing undervolting operations in an easy way. Undervolting is not a dangerous operation – it should not damage the processor (Kalau et al. 2016). If the processor is assigned too low voltage, the component will report the misconfiguration to the BIOS and shut down the computer. The voltage configuration is stored only in the operating system (a profile is created which starts with the operating system). This means that if the voltage is set too low during testing and the changes are not saved (only the test profile is set), then after turning the computer off and on everything will return to normal. However, it is important to thoroughly test the created profile before it is permanently saved and set as the default profile. If by mistake the voltage is set to low and the profile is saved, the operating system will use it every time it starts – this means that if the incorrect profile causes the computer to shut down, the computer will reboot every time the system is started. In that case, the misconfiguration can be repaired by running the system in emergency mode and removing the profile used. When undervolting the processor, it should be loaded with synthetic tests (e.g. with the Small FFT test of the Prime95) (Kalau et al. 2016). An example of a synthetic test is shown in the Figure 1.

Processor undervolting should be done in steps. In the first step, lower the voltage values on the core by 20 mV and see if the machine is stable. Then the voltage should be lowered by another 20 mV (after lowering the voltage by 100mV, it should be lowered step by step by 10 mV) until the machine becomes unstable. After selecting the appropriate value, set the same value for the processor cache. If an error occurs after the processor cache voltage has been lowered, the cache voltage should be slightly increased by e.g. 10 mV or 20 mV and the tests should be repeated. It is also worthwhile to do undervolting of the integrated graphics processor (iGPU), but the reduction is usually much smaller than the core and cache (usually about half of the reduction of core and cache).

Processor manufacturers provide tools to customize processor performance. For Intel processors, Intel XTU (Fig. 2) can be used, while for AMD processors AMD Ryzen Master can be used. There are third party programs, i.e. ThrottleStop (Fig. 3), that allow the change of CPU clock parameters and voltages, but these are not applications designed by CPU manufacturers and the configuration made in them can be unstable or harmful to the chip.

The undervolting operation can also be performed by changing the processor's voltage in the BIOS. Unfortunately, on most motherboards, the firmware is limited and does not offer this option. It should also be noted that if the wrong configuration is used and saved in the BIOS memory, irreparable damage to the computer is possible.

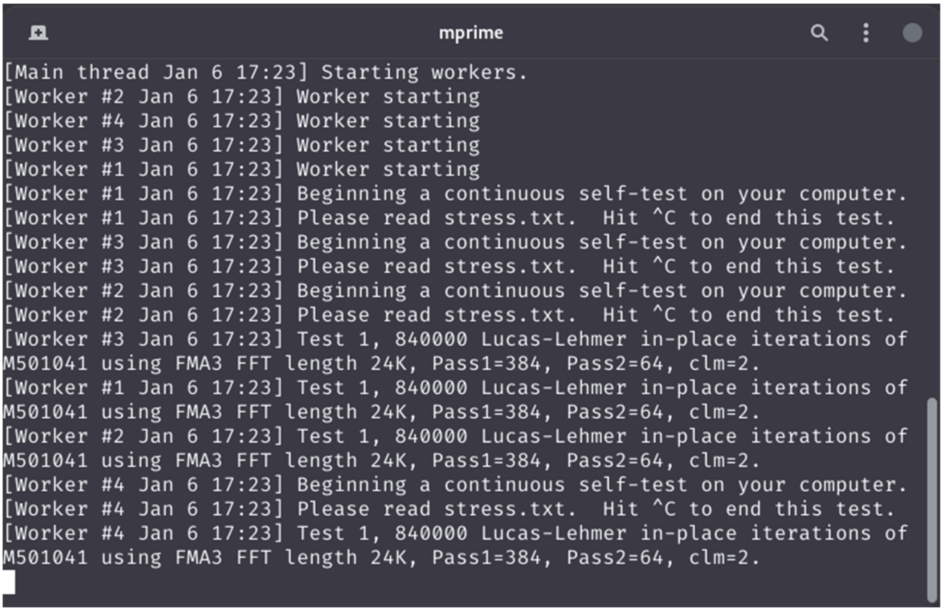

Fig. 1. Synthetic test with Prime95

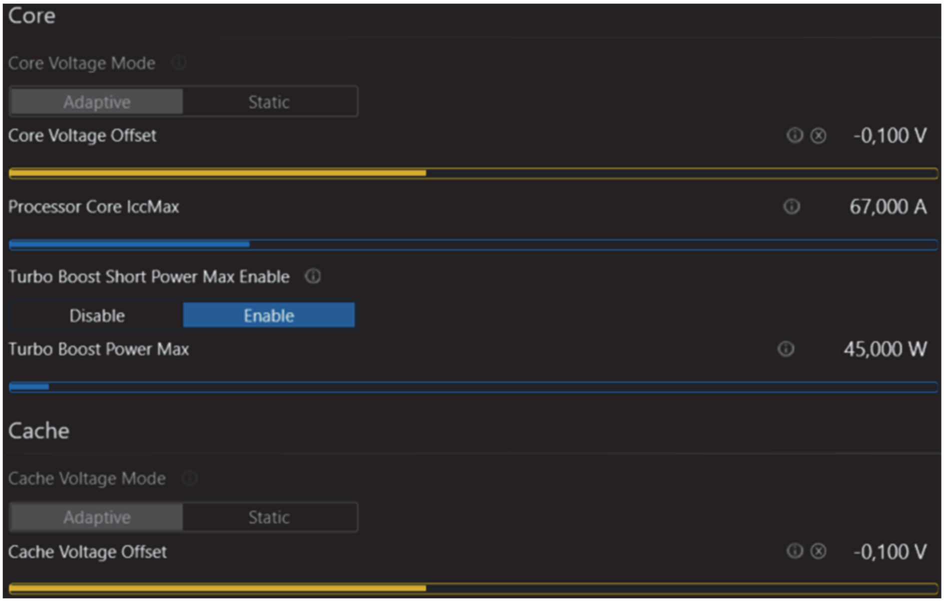

Fig. 2. Intel XTU interface – shows the common software options that are used for undervolting

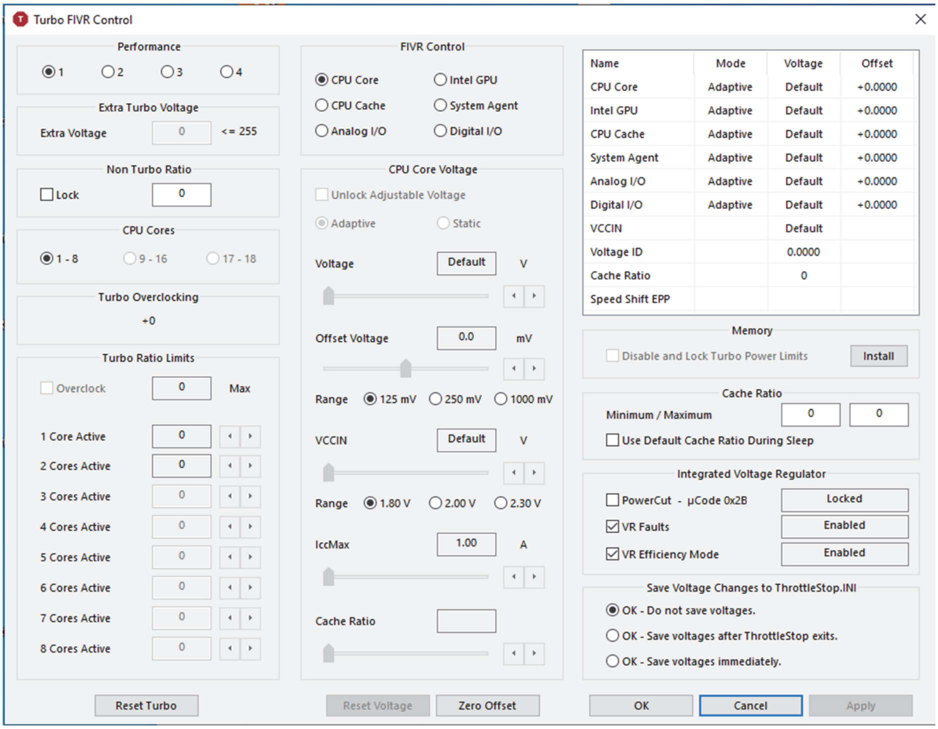

Fig. 3. ThrottleStop interface

2. Testing workstation

To assess the efficiency and applicability of undervolting, computers located in universities laboratories were used. There were two laboratories, each equipped with 20 identical computer workstations in terms of hardware configuration. The laboratories were used by students of a university in Gdańsk. One of the computer laboratories was used for computer graphics classes and the other one for application programming classes. The use of two laboratories allowed to compare results of undervolting for less loaded computers (programming classes) and for heavily loaded computers (computer graphics classes).

In computer laboratories, the standard computer unit is equipped with Intel Core i5-6600 processor cooled by SilentumPC Spartan Pro heatsink with a single fan, Patriot RAM (two units with a total capacity of 8 GB), HDD, SilentumPC Vero M1 power supply.

The maximum power consumption of a single RAM is 3.7 W (average consumption is about 1.0-1.5 W), power consumption of HDD is 6 W. When calculating the theoretical power consumption of a computer workstation, the power consumption of the monitor and peripheral equipment should also be taken into account. In this case, the testing workstation's monitor has an average power consumption of 25 W. The peripherals, i.e. mouse and keyboard, are connected to USB 2.0, so the maximum consumption of each of these peripherals is 0.5 W. The maximum power consumption of a cooling system equipped with three fans is 9 W (the maximum power consumption of a single fan is estimated at 3 W), however, it should be noted that the maximum power consumption occurs only when the fans operate at maximum speed – the average power consumption of the fans can be estimated at 3-4 W.

The Intel Core i5-6600 processor has a 65W TDP (Thermal Design Power) (Intel ARK). It is a 4-year-old unit (premiered in the third quarter of 2015) made in 14 nm lithography, with 4 cores and 4 threads at 3.3 GHz base clock (in 3.9 GHz Turbo mode).

3. Processor undervolting

The assessment of undervolting effectiveness and possibilities was made in to experiments on computer units described above. The first experiment can be described as static and the second as a dynamic. In the static experiment, the possibility of undervolting was evaluated on the basis of the specification of the computer parts in the computer unit. Knowing the specification of a computer unit, it is possible to assess its potential in terms of undervolting and potential energy gain. In the second experiment, the efficiency of undervolting was studied in two university laboratories – one with programming classes and the second with computer graphics classes. This experience consisted of recording the laboratory computers' processor load and measuring the electricity consumed. The experiment was carried out for computers with not undervolted processors and then repeated after performing the undervolt.

In a static experiment, the processor was undervolted. Voltage Offset values were reduced by 20 mV in steps until the value at which the processor stopped working properly was reached. After a 240 mV voltage reduction, processor errors occurred during the synthetic tests. Core Voltage Offset and Cache Voltage Offset were set to -220 mV and Processor Graphics Voltage Offset to -110 mV. After several hours of synthetic tests, this setting was found to be fully stable. The operation was performed with Intel Extreme Tuning Utility (Intel XTU). Figure 4 shows the profile created.

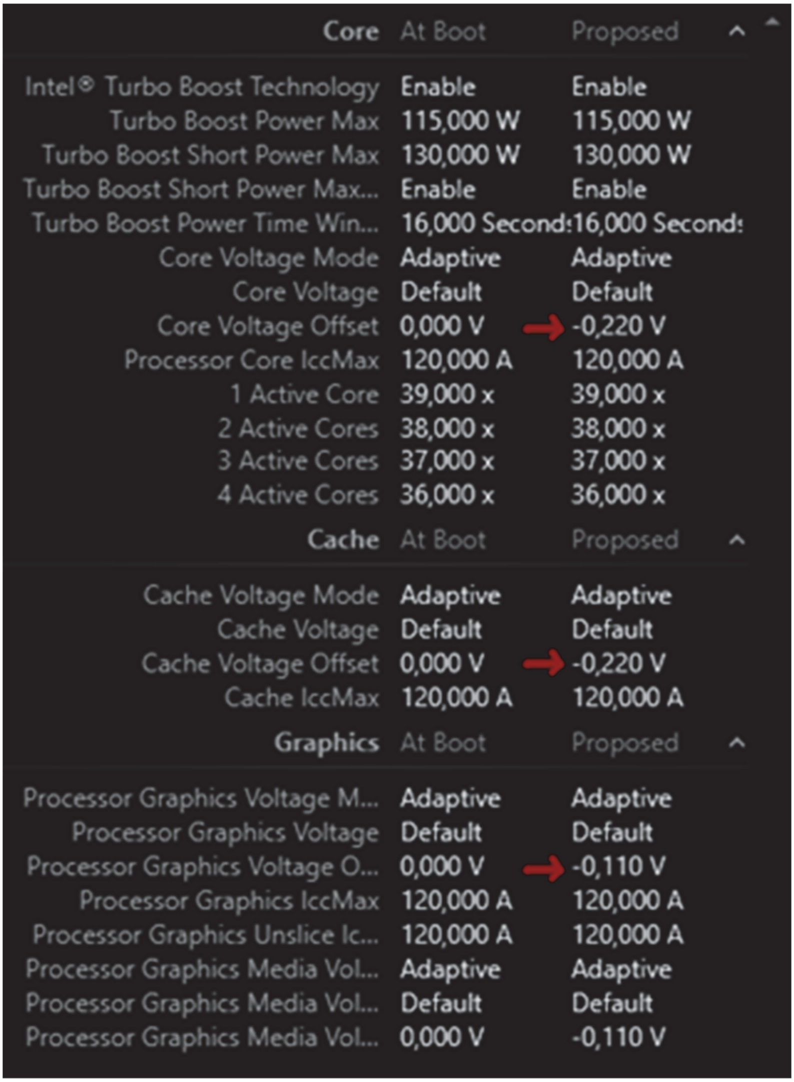

Fig. 4. XTU profile of Intel Core i5-6600 processor, where Proposed shows values of created test profile

The reduction of the voltage on the processor's core and the processor's cache by 220 mV resulted in a significant reduction of the processor power consumption and the amount of heat generated. Figure 5 shows a comparison of power consumption and temperatures.

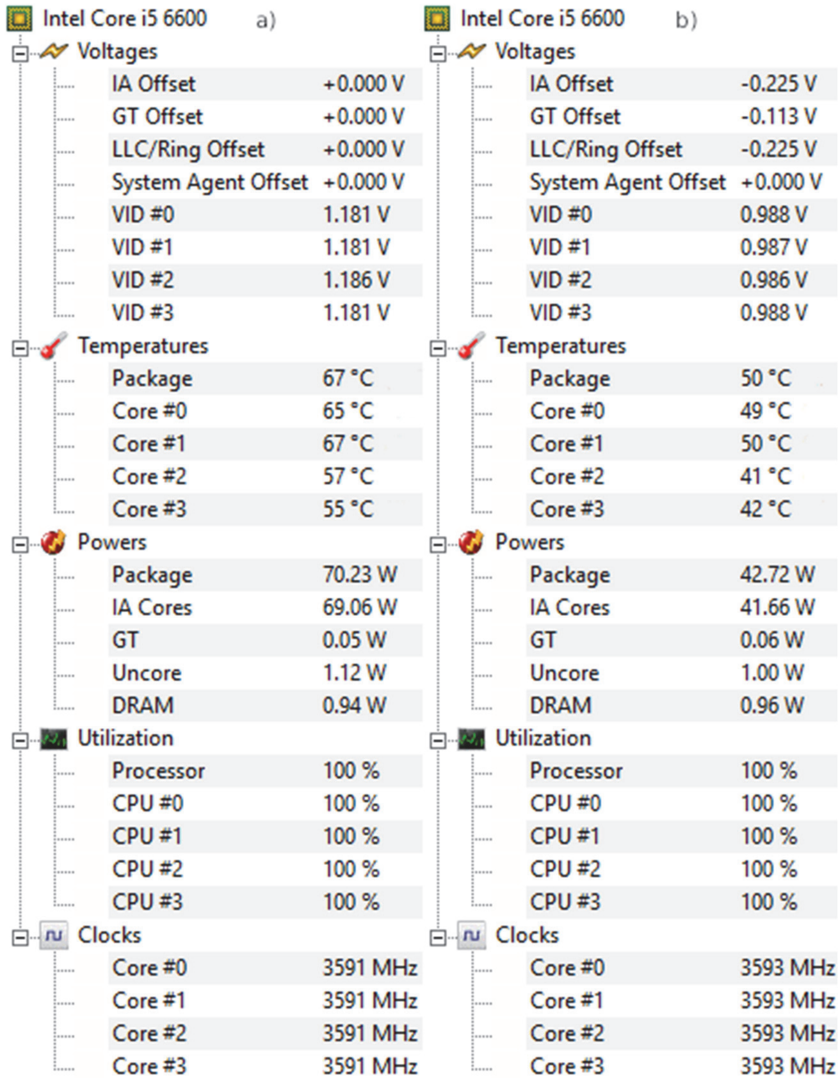

Fig. 5. Comparison of power consumption and temperature of the i5-6600 CPU at default voltage (a) and reduced voltage (b) by 225 mV on the core and cache and 113 mV on the iGPU

As shown in Figure 5 before undervolting, the processor, when loaded with a set of synthetic tests (Prime95, Small FFT test) on all cores, had a power draw close to 70 W (Powers → Package indicator) and maintained a temperature of 67°C (Temperatures → Package indicator) on the cores. The processor has been able to achieve 3600 MHz at all cores – this is the maximum clock speed that this unit can achieve (3.9 GHz Turbo mode is activated when only one core is loaded). This means that during the test, the processor was not restricted by security features (there was no Thermal Throttling, Power Throttling and Current Throttling Limit). After undervolting (IA Offset, GT Offset, LLC/Ring Offset indicator) core and cache voltage was reduced by 220 mV (in fact 225 mV) and iGPU by 110 mV (in fact 113 mV) and with all cores loaded with the same set of tests, the processor kept the clock speed at the same level, but with a power consumption of 43 W and core temperature of 50°C.

This means that after undervolting, the processor is able to perform tasks with the same performance, but at maximum load it draws 27 W less power and generates less heat.

Of course, the difference in power consumption will be different for a different degree of load. For medium load (in CAD programs), the undervolted CPU drew about 16 W less. Figure 6 shows a comparison of power consumption at medium load.

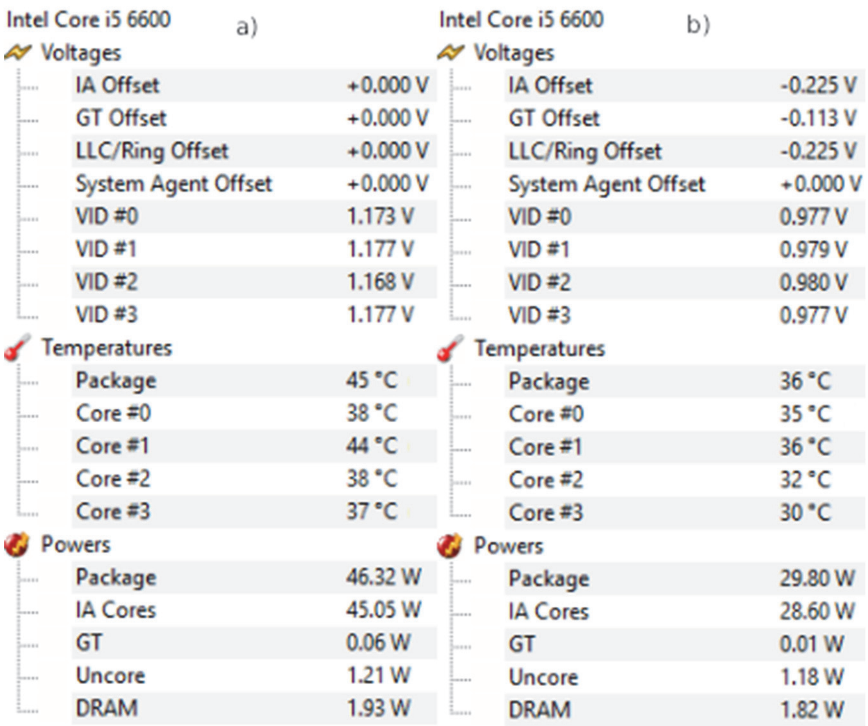

Fig. 6. Comparison of power consumption of i5-6600 CPU on medium load; a) in factory configuration, b) after undervolting

4. Processor undervolting in laptops

Not all computer laboratories are equipped only with desktop computers. Often laptops are used. Laptop processors are built differently than desktop processors. Manufacturers must take into account battery life and low efficiency cooling system (related to compactness of construction). For this reason, laptop processors are built as energy-efficient units. Unfortunately, the energy-efficient design of the processor is usually associated with a lower core clock speed and fewer threads. Undervolting operations on these processors are usually significantly more difficult, due to the already low base voltage. Undervolting of such processors is possible, but it is marginal and usually does not produce tangible results. However, there are series (marked as HQ) of processors for laptops, which are characterized by high performance – in this case the energy efficiency has been put aside. These notebooks are mainly designed for calculations, graphic processing, 3D modeling and simulation studies. These types of laptops are used in the computer laboratories of universities. To show the effectiveness of undervolting processor of such computer devices, the Intel i7-7700HQ processor with TDP of 45 W (Intel ARK). was also undervolted.

For undervolting purposes, Core Voltage Offset has been changed to -0.100 V, Cache Voltage Offset to -0.100 V and Processor Graphics Voltage Offset to -0.055 V. Figure 7 shows the profile created.

As can be seen in Figure 8 before undervolting, the processor, with power consumption close to 45 W and with all cores loaded with a set of synthetic tests (Prime95, Small FFT test), achieved a clock speed of 2700 MHz. After undervolting (IA Offset, GT Offset, LLC/Ring Offset indicator) core and cache voltage was reduced by 100 mV (in fact 102 mV) and iGPU by 55 mV (in fact 56 mV), with all cores loaded with the same set of tests, the processor kept the clock speed of 3000 MHz with the same power consumption.

This is due to the compactness of laptops. Unfortunately, laptop cooling systems, due to the small size of the fans and heat sink, do not conduct heat away from the processor efficiently enough. For this reason, there is the mechanism of Thermal Throttling – as a result of too high processor temperature, its clock speed are reduced (Liu et al. 2018, Zhang et al. 2019). Undervolting reduces the heat emitted by the processor, so the processor is able to maintain a higher clocks speed before the Thermal Throttling mechanism is activated.

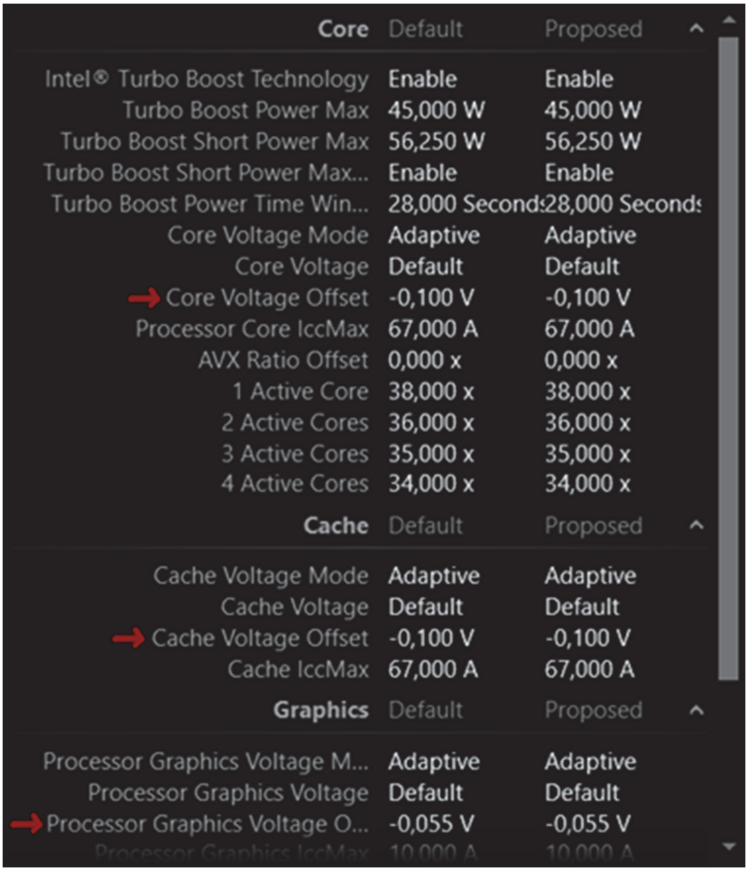

Fig. 7. XTU profile of Intel Core i7-7700HQ processor, when Default and Proposed values are the same, the profile is saved and will be used after system reboot

Figure 8 shows a comparison of the power consumption, clock speed and processor load during synthetic tests before and after undervolting.

This means that after undervolting, the processor runs at a higher clocks speed and is able to perform tasks faster. If the processor was running on the same clocks speed as before undervolting, it would draw less power. Unfortunately, in reality, as a result of undervolting, the laptop's maximum processor temperature reached will not be lowered. Undervolting will enable the processor to work more efficiently, but despite the reduction of generated heat, the cooling system will still not be able to dissipate it effectively enough. However, the lifetime of the processor will be significantly improved as the processor will perform calculations faster and run at high temperatures for shorter periods of time.

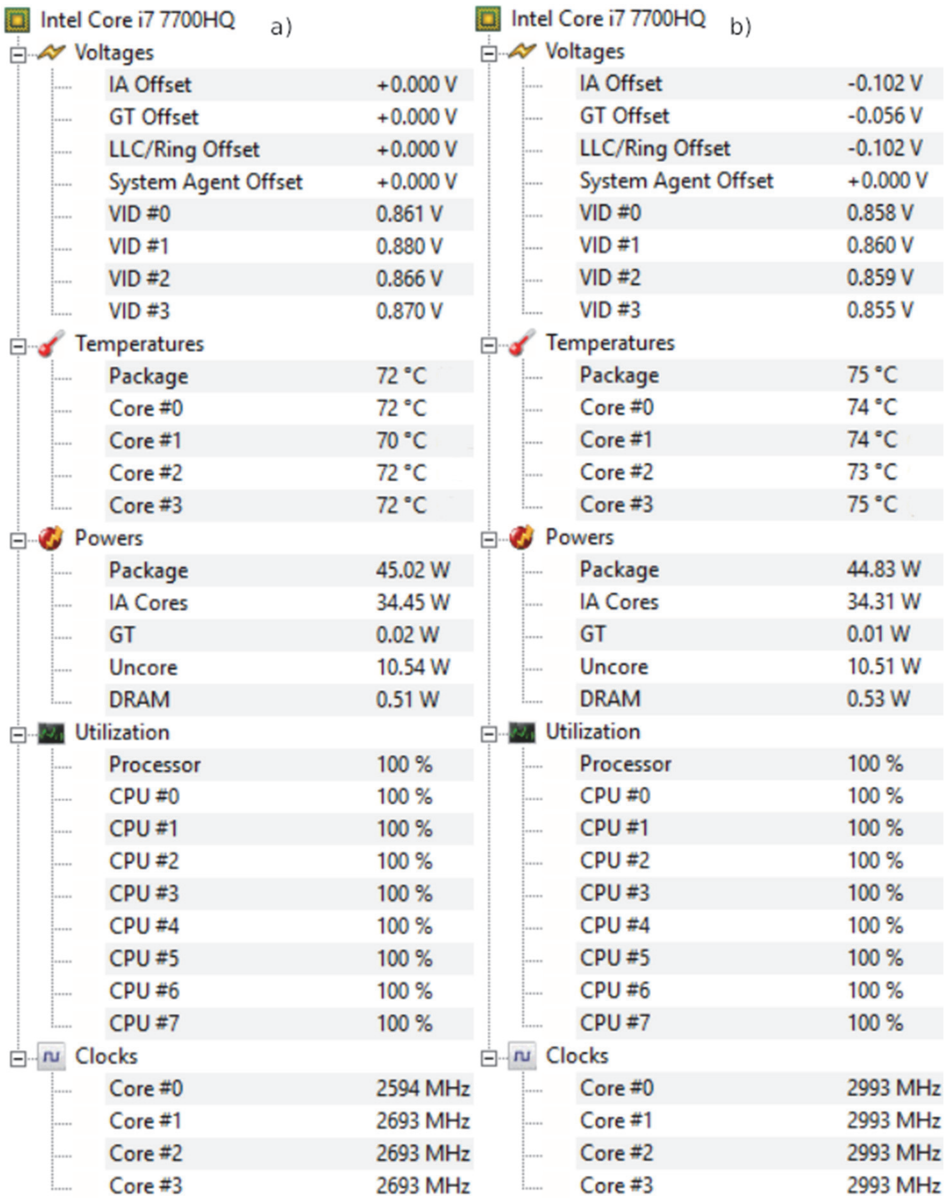

Fig. 8. Comparison of i7-7700HQ CPU performance at default voltage (a) and reduced voltage (b) by 102 mV on core and cache and 56 mV on iGPU

5. Environmental research

For the purpose of verifying the influence of undervolting on the power consumed by the computers in the computer laboratories, the power consumption of the computers in the laboratory without undervolting and with undervolting was measured.

Two computer laboratories were selected to carry out the experiments and their computers' power consumption was measured. In the first laboratory programming and computational techniques (conducted in the Matlab environment) classes took place. In the second laboratory there were graphic processing and CAD modeling classes. Both laboratories were equipped with a power meter covering only stationary units of computer workstations, excluding monitors and projectors located in the rooms.

In order to facilitate the measurement of power consumption, unnecessary components, i.e. optical drives, additional PCI-E expansion cards, etc., have been disconnected from computers. Peripheral devices, i.e. keyboard, mouse and USB flash drive, are connected to active USB hubs with separate power supply. To avoid measurement error, the theoretical power consumption of a single computer unit was calculated before testing, based on the manufacturer's power consumption data of each component. Calculations were made in different states (idle, load, heavy load) of the CPU without and with undervolt. The values thus established were a model to which the results obtained at later stages of research were compared.

The next step was to carry out measurements for computers with a processor factory configuration and for computers with a undervolted CPU. The research was conducted over a period of two months (October and November 2019). The tests included 160 hours of computers operation – 80 hours of computers with CPUs on factory configuration operation and 80 hours of computers with undervolted CPUs. The results of power consumption were obtained from two computer laboratories, which differ in the tasks performed by the students and the intensity of processor use during these tasks. The research has shown that the computers in the second laboratory for graphics and CAD modeling classes consume more power.

With the prepared model, for 80 hours of measurement from each laboratory, only the measurement time was taken into account, in which the computers performed intensive work and the number of used computers in the rooms was the same. The measurement time during which the computers were powered on but not used or the processor was in a state of inactivity or low activity was discarded. In this way, the measurements were limited to 50 hours of intensive processor usage of computers in each laboratory.

Figure 9 shows a diagram of the power consumption of computers from the first laboratory after CPU undervolting compared to computers' power consumption from the first laboratory before CPU undervolting.

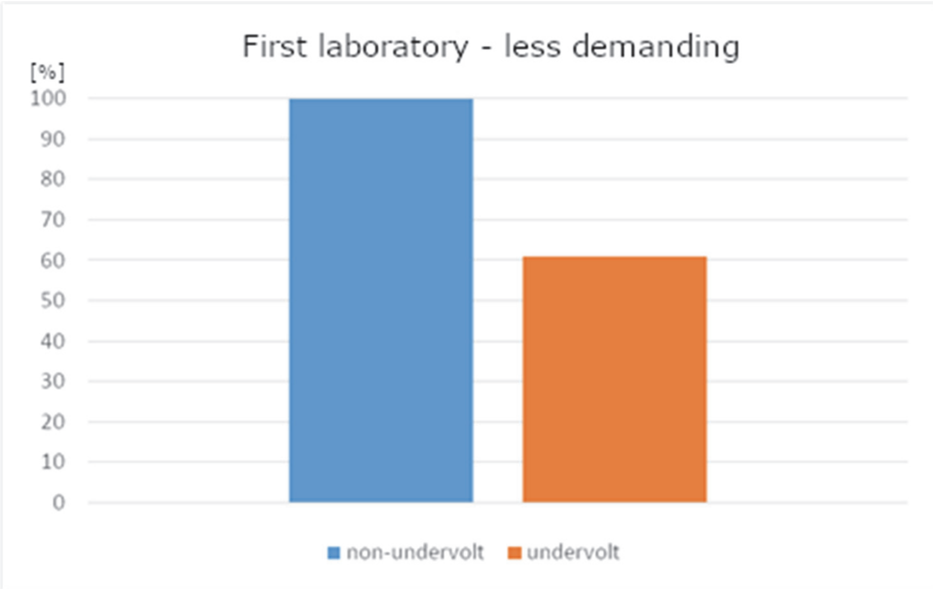

Fig. 9. Power consumption of computers after undervolting compared to computers before undervolting – first laboratory (programming and computational techniques)

Figure 10 shows the power consumption of computers from the second laboratory after CPU undervolting compared to computers' power consumption from the second laboratory before CPU undervolting.

Analyzing the results shown in Figures 9 and 10, it was noted that the energy gain of a computer unit with undervolted CPU is greater when computers perform tasks intensively and the processor is continuously loaded – in the second laboratory, there were graphics and CAD modelling classes that required continuous rendering, which intensely and continuously loaded the processor. In the case of tasks with lower processor intensity, the profit is lower – in the first laboratory, there were programming and computational technique classes, which require calculations only when compiling source code or running scripts.

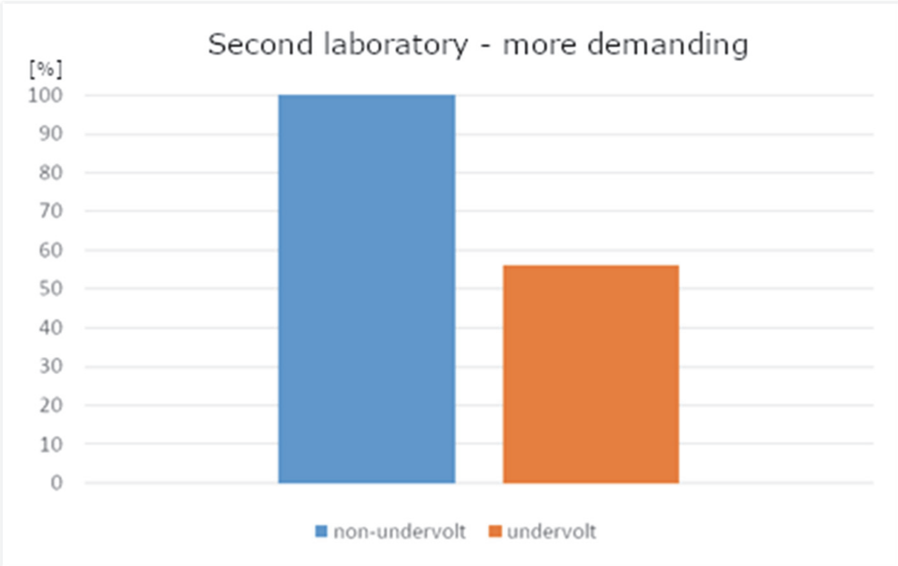

Fig. 10. Power consumption of computers after undervolting compared to computers before undervolting – second laboratory (graphic processing and CAD modeling)

6. Conclusion

Undervolting allows reducing CPU voltage. There are many reasons why this is desirable. The voltage reduction leads to a reduction in power consumption. In the case of a processor, the energy drawn is given away in the form of heat – this means that a reduction in voltage reduces the generated heat. Lowering the temperature in which the computer operates leads to benefits in relation to the service life of the component being used – the processor running at lower temperatures will degrade much slower. Lowering the temperature also relieves the cooling system. In the case of passive cooling there will be no difference in power consumption. However, with active cooling, the power consumption will be reduced. Each active cooling system is equipped with fans whose task is to take the heat from passive elements of the cooling system and transfer it outside the computer unit. With undervolting, the processor emits much less heat, which means that the cooling system will be able to dissipate the heat at reduced fan speed. The fans draw less power at lower rotating speed.

Reducing the heat generated by the processor also affects other computer components. In most computers, air circulation is common to all elements. This means that the air heated by the processor spreads in the central unit increasing the operating temperature of the other components, thus shortening their service life.

For laptops with insufficient cooling capacity, CPU performance is limited due to temperature limits. When the temperature limit is reached, the processor's clock speed is reduced to the level where the processor emits as much heat as the cooling system is able to discharge. Undervolting reduces the amount of heat generated by the processor, allowing the processor to run at higher clocks speeds before the temperature limits are reached. This means that by performing undervolting operations on the processor in the laptop, the performance and speed of completing the tasks is increased, which results in shortening the processor's operation at high temperatures time.

The use of undervolting is particularly important in school and university computer laboratories and in enterprises, because limiting the heat generated by multiple computer workstations in the same facility has a real impact on room temperature. The noise generated by fans of cooling systems installed in computers is also reduced. Reducing room temperature and noise can have a positive impact on the comfort of employees and students, and will save on air conditioning costs. With a large number of computers in the room, the reduction in power consumption is significant and brings about measurable savings. Increasing the life of computer components reduces the cost of repair or possibility of hardware replacement.

Undervolting should also be used in houses and flats. The benefit of reducing the electricity consumption of a single computer station may not be convincing enough, but it is worth noting that more than one computer is very often used in a single house or flat. At the scale of a block of flats or a housing estate, the profit from the electricity saved would be significant. However, for the household members, it may be more important to reduce the heat generated than the profit from reduced power consumption. Especially in summer, in a small room with a few hours of intensive use of the processor (in a home environment it can be computer gaming) the heat generated can cause discomfort.

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Abstract

This paper presents a method of lowering the processor's voltage and temperature in which the computer operates by performing an operation called undervolting. By using undervolting it is possible to reduce electricity consumption and the amount of heat generated by computer workstations by up to 30%. This problem is particularly relevant for institutions that use a large number of computers. The more the computers are subjected to the higher computational load, the more effective the mechanism of undervolting is. Undervolting the processor does not reduce its performance, but lowers its operating temperature, has a positive impact on its life span and power consumption. Maintaining a low temperature of operation for computer hardware is essential to reduce operating and repair costs. The paper also presents the results of environmental research aimed at assessing the validity and effectiveness of undervolting.

Keywords:
undervolting, energy saving, electric energy, power consumption, generated heat, processor

Analiza wykorzystania undervoltingu do redukcji zużycia energii elektrycznej w urządzeniach komputerowych i oddziaływania na środowisko

Streszczenie

W pracy przedstawiono metodę obniżania napięcia procesora i temperatury pracy komputera poprzez wykonanie operacji zwanej undervoltingiem. Przez zastosowanie undervoltingu można obniżyć nawet o 30% zużycie energii elektrycznej i ilość wydzielanego ciepła przez stanowiska komputerowe. Problem ten jest szczególnie istotny w przypadku instytucji, które korzystają z dużej liczby komputerów. Skuteczność mechanizmu jest tym większa im komputery poddane undervoltingowi są bardziej obciążone obliczeniowo. Wykorzystywanie undervoltingu w konfiguracji procesora nie zmniejsza jego wydajności, a obniża jego temperaturę pracy, wpływa pozytywnie na jego żywotność i zużycie energii elektrycznej. Utrzymanie dobrej kultury pracy sprzętu komputerowego jest kluczowe, by obniżyć koszty eksploatacji oraz napraw. W pracy przedstawiono również wyniki badań środowiskowych, których celem była ocena zasadność i efektywności stosowania undervoltingu.

Słowa kluczowe:
undervolting, oszczędzanie energii, energia elektryczna, pobór prądu, generowane ciepło, procesor