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# AC POWER REGULATION TECHNIQUES FOR RENEWABLE ENERGY SOURCES

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***Abstract.*** *This article explores different AC power regulation techniques that can be employed to optimize the output of renewable energy sources, such as solar and wind power systems. The article provides an overview of the challenges associated with regulating AC power output from renewable sources and examines various techniques that can be used to improve the performance of power regulation systems. These techniques include voltage control, phase control, reactive power compensation, and power factor correction. The article also discusses the benefits and limitations of each technique, as well as their potential applications in renewable energy systems. Overall, this article provides valuable insights for engineers and researchers working to optimize power auto consumption in renewable energy systems.*

**Keywords**: ac power regulators, pulse width modulation converters, renewable energy systems

## TECHNIKI REGULACJI MOCY ODBIORNIKÓW AC DLA ODNAWIALNYCH ŹRÓDEŁ ENERGII

***Streszczenie.*** *W tym artykule omówiono różne techniki regulacji mocy prądu zmiennego, które można wykorzystać do optymalizacji produkcji energii ze źródeł odnawialnych, takich jak systemy energii słonecznej i wiatrowej. Artykuł zawiera przegląd wyzwań związanych z regulacją mocy wyjściowej prądu przemiennego ze źródeł odnawialnych i analizuje różne techniki, które można wykorzystać do poprawy wydajności systemów odnawialnych źródeł energii. Techniki te obejmują sterowanie napięciem, sterowanie fazą, kompensację mocy biernej i korekcję współczynnika mocy. W artykule omówiono również zalety i ograniczenia poszczególnych technik, a także ich potencjalne zastosowania w systemach energii odnawialnej. Artykuł zawiera cenne informacje dla inżynierów i badaczy pracujących nad optymalizacją auto konsumpcji energii elektrycznej w systemach energii odnawialnej.*

**Słowa kluczowe**: regulatory mocy prądu przemiennego, przetwornice modulacji szerokości impulsu, systemy energii odnawialnej

## Introduction

Renewable energy sources, such as solar and wind power plants, have become increasingly popular due to their numerous benefits over traditional fossil fuels. However, one of the main challenges in harnessing these energy sources is their inherent variability and intermittency. This means that their output power levels can fluctuate unpredictably over time, making it difficult to maintain a stable and consistent electricity supply to the grid.

To address this issue, various AC power regulation techniques have been developed to effectively manage fluctuations in renewable energy sources and ensure a stable power supply. These techniques involve the use of advanced power electronics and control systems that can efficiently convert, condition, and regulate the AC power generated from renewable energy sources.

This article provides an overview of some of the most common AC power regulation techniques used in self-consumption devices found in photovoltaic systems. The operating principles, advantages, and limitations of each technique will be discussed, along with their potential applications in various renewable energy systems. By the end of this article, readers will have a better understanding of how AC power regulation techniques can impact the quality of energy in self-consumption devices utilized within renewable energy systems.

## 1. The essence of power/voltage regulation of AC receivers powered from renewable energy sources

Voltage stability is an important parameter of the state of the power grid. According to the standards determined individually for each country, its value must be within the specified standards. For example, in Poland, according to the PN-EN 50160 standard, the correct voltage value should be within the range of 207-253V RMS (230V nominal).

In figure 1, a voltage graph for one of the three phases is presented. The measurement was conducted on April 11, 2023, using an Agilent 34461A multimeter, with measurements taken at 1-second intervals. The measurements were taken in a small town where several photovoltaic installations are installed. The graph shows numerous voltage fluctuations which can be associated with the activation of various devices. From the chart, it can also be observed that the voltage value is higher than the nominal voltage. This is due to the injection of energy into the grid by photovoltaic installations. During peak hours, the voltage value exceeds the permissible limits (253 V). This may be caused by improper settings of some inverters in residential photovoltaic installations. Sudden fluctuations in the grid voltage during hours of electricity overproduction can also be associated with the cascading shutdown of inverters due to the detection of excessively high voltage on any phase. From the perspective of energy suppliers, this is a significant issue, especially during the summer period.

Therefore, it appears necessary to use devices that increase self-consumption of electrical energy [2]. Typically, these are various types of domestic hot water tanks equipped with a high-power heater with electronic control system to regulate temperature. The heater is activated during the production of electrical energy by the photovoltaic installation. More expensive solutions are enhanced with power control systems that adapt it to the current production of the photovoltaic installation.

The second figure shows a voltage chart on each of the phases on May 21, 2023, recorded by the SoFar SF4ES005 inverter. From the chart, one can read The excessive voltage level and its fluctuations are independent on each phase. Three-phase inverters shut down energy production on all phases if voltage value standards are exceeded on even one of them. This results in abrupt shutdowns of photovoltaic installations, leading to sudden changes in grid voltage across all phases. This causes losses in energy production for prosumers and is another reason to implement advanced self-consumption systems with sophisticated control systems.

Another important parameter is the amount of additional harmonics introduced into the power grid. This is a very important parameter due to the need to reduce voltage distortions described in the electrical standards applicable in various countries (in Poland, PN-EN 61000). The most problematic harmonics are those with low frequencies due to issues related to designing LC filters or EMI filters [4]. The cutoff frequency of low-pass reactive (LC) filters is described by the equation [6]:

$$f_{gr} = \frac{1}{\pi\sqrt{LC}} \tag{1}$$

For a frequency of 50 Hz, both the required capacitance and inductance must have large values. Furthermore, to improve the amplitude response of the filter (for passive filters, the roll-off rate is typically 20dB/decade), it is necessary to combine them cascadingly. The higher the values of the first 10 harmonics, the more complex the problem becomes when designing a filter. Capacitors with high capacitance cause a phase shift between current and voltage, which in turn increases the reactive power component.

Each electricity receiver changes the parameters of the power grid to a greater or lesser extent. A particular problem for power grids are small photovoltaic installations in a prosumer system, and potentially new challenges in the form of high-power receivers where power regulation is necessary [1]. Therefore it is so important to choose the right control method for a specific solution.

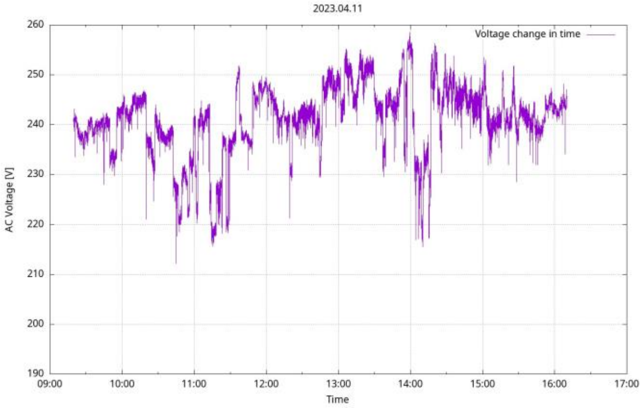


*Fig. 1. Voltage waveform measured on one of the three phases made on April 11, 2023 using the Agilent 34461A multimeter*

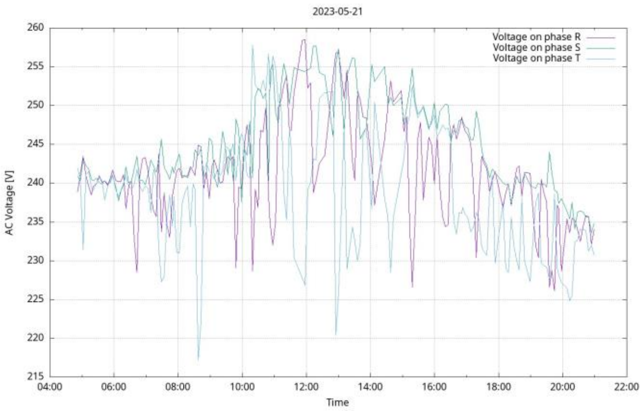


*Fig. 2. Voltage waveform on each of tree phase reported by Sofar SF4ES005 inverteter on April 11, 2023*

## 2. Power regulation techniques for AC loads

The power generated by renewable energy systems is highly variable over time. This is especially noticeable in photovoltaic systems when on a sunny day the output voltage is high enough that the inverter shuts down to meet the requirements of the grid. This causes a reduction in energy production and, at the same time, voltage spikes in the transmission grids. To prevent this, various types of systems that increase self-consumption of energy are used. They usually act as thermal energy storages in which electrical energy is converted by heaters into thermal energy. These heaters are used mainly in boilers to heat up domestic hot water. The simplest method of increasing self-consumption is a system in which the heater is simply switched on when the energy is sent to the grid. This may cause an unnecessary load on the transmission lines due to the incorrect adjustment of the heater power to the current production of electricity by photovoltaic panels. Therefore, in more advanced systems, the power of the energy receiver is regulated so that the total energy consumed by the house is equal to 0 if it posiible. Usually, power regulation is accomplished by altering the output voltage. This can be achieved by converting alternating current to direct current, and then regulating the voltage using a PWM controller or by converting it back to AC voltage using an inverter [5]. There are three main techniques for controlled power regulation of AC receivers [3].

### 2.1. Phase Angle Control

Phase Angle Control is a widely used method for regulating the power delivered to AC loads. This method involves adjusting the firing angle of a thyristor, triac or other solid-state switch in the AC circuit to control the amount of power delivered to the load. By adjusting the phase angle, the effective voltage and current delivered to the load can be controlled.

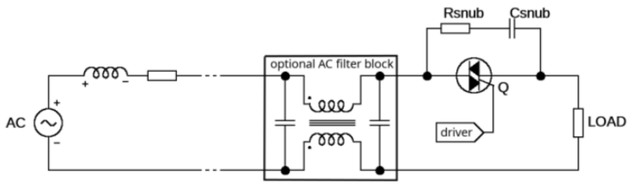


*Fig. 3. Circuit layout of typical AC power regulator for Phase Angle Control or Burst Fire control*

One of the primary advantages of Phase Angle Control is its simplicity and low cost. A typical circuit layout of the regulator is shown in Fig. 3. Compared to other methods such as PWM control, Phase Angle Control requires fewer components and can be implemented using relatively simple control circuits. Phase Angle Control method has good power resolution and fast response to set-point changes. Examples of the output voltage waveforms are shown in Fig. 4.

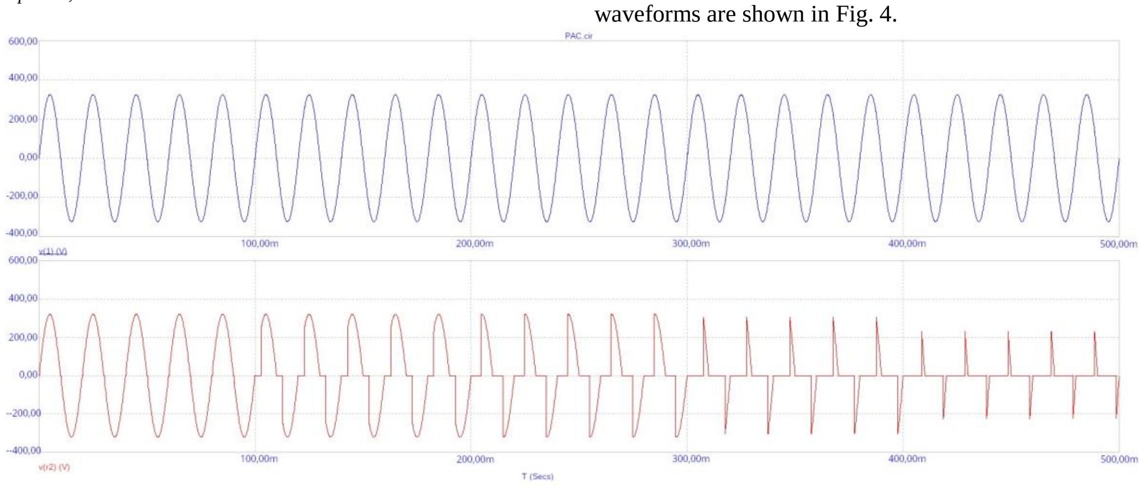


*Fig. 4. Input voltage and load voltage waveforms for 100%, 75%, 50%, 25% load for Phase Angle Control method*

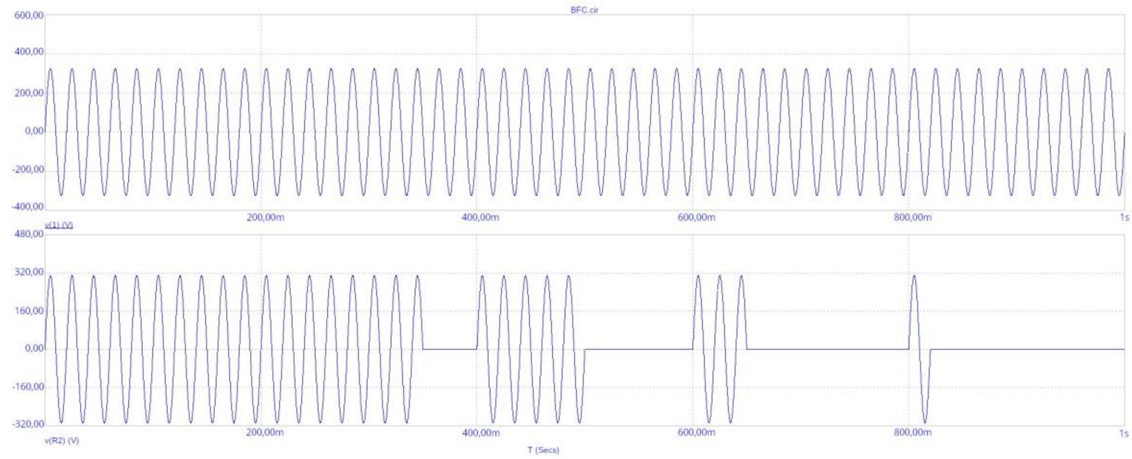


*Fig. 5. Input voltage and load voltage waveforms for 100%, 75%, 50%, 25% load for Burst Fire Control method*

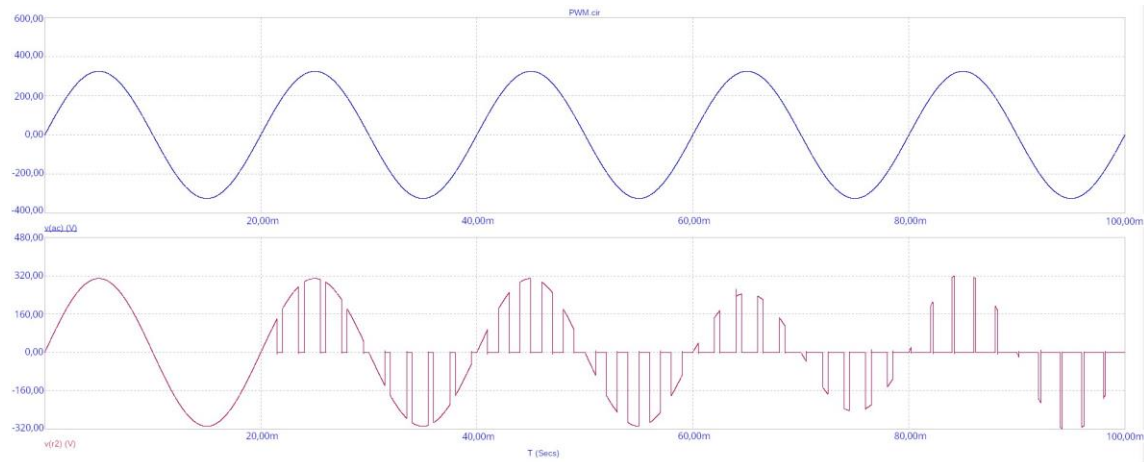


*Fig. 7. Input voltage and load voltage waveforms for 100%, 75%, 50%, 25% and 10% duty cycle for PWM method*

It can be seen that for a duty cycle below 50% the waveforms are heavily distorted. This can cause problems with the power supply of devices that are passive inductive or capacitive. Morever, there are some limitations to Phase Angle Control that should be considered. One major issue is the distortion of the AC waveform, which can lead to increased harmonic content and reduced power factor. To address these issues, several variations of Phase Angle Control have been developed, such as modified phase control and burst firing. These techniques involve adjusting the duration of the thyristor firing pulses to minimize distortion and improve efficiency.

## 2.2. Burst Fire Control

Burst Fire Control is a method of power regulation that is commonly used in AC power control applications. The circuit shown in Fig. 3 can be used for the regulation of output power. In Burst Fire Control method, the AC waveform is divided into a series of pulses, with each pulse being triggered by a separate thyristor, triac or other switching device. The duration of each pulse, or "burst", is controlled to regulate the power delivered to the load.

Fig. 5 shows the voltage waveform at the output of the Burst Fire Control for duty cycles of 100%, 75%, 50%, 25% and 10%.

One advantage of Burst Fire Control is its simplicity and cost-effectiveness. Compared to other AC power control methods, such as Phase-Angle Control, Burst Fire Control requires fewer components and less sophisticated control circuitry. This makes it a popular choice for applications where cost and simplicity are crucial factors. However, Burst Fire Control also comes with some disadvantages. This method can generate significant harmonic distortion in the input waveform, especially, which can cause issues with other equipment in the same electrical system. Moreover, due to its nature, it offers very low resolution. Additionally, this method can only be used for resistive loads.

## 2.3. Pulse Width Modulation

The basic principle of PWM (Pulse Width Modulation) regulators relies on cyclically turning on and off electronic switches, such as transistors or thyristors, to generate rectangular pulses. The ratio of the on-time of the switch to the total period determines the duty cycle of the PWM signal. A higher duty cycle corresponds to a longer pulse duration relative to the period, resulting in a higher effective voltage or current. The schematic diagram of an example PWM regulator is shown in Fig. 6.

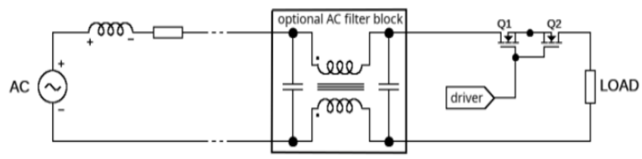


*Fig. 6. Circuit layout of typical AC power regulator for PWM control*

In the simplest version, the regulator consists of two MOSFET transisotrs switched on simultaneously. Compared to the Phase Angle Control regulator, it requires the use of a more complicated gate driver system. Fig. 7 shows the voltage waveform at the output of the pwm controller operating at 1 kHz for duty cycles of 100%, 75%, 50%, 25% and 10%.

The PWM control regulator operates at a high frequency (above 30kHz), thanks to which disturbances in the power grid are easier to filter out. Morever, the PWM controller does not cause flickering as in the case of the Burst Fire Control controller. This type of controllers can work with resistive loads, but more importantly, after applying appropriate LCL filters, also with inductive or capacitive loads.

## 3. Simulation results

The simulations were conducted using Microcap 12 software. In the simulations, the impact of power regulation methods on distortions appearing in the power grid was compared. For this purpose, a resistive load with a rated power of 2 kW was connected to the control system. The research was carried out for 6 regulation cases: 25%, 50%, 75%, and 100% for voltages ranging from 217V to 253V RMS (in accordance with PN-EN 50160).

Charts 8-10 depict Harmonic Distortion Analysis plots for regulators at 50% load power regulation and voltages ranging from 217V to 253V RMS. The analysis presents the first 10 harmonics appearing on the utility side of the power grid.

In figure 8, the result of the Phase Angle Control regulator's operation is presented. The third harmonic of the signal – 150 Hz, has an amplitude of 5.24V, which corresponds to 1.7% of the grid voltage value. The successive harmonics had the following values: 5th – 1.6 V, 7th – 1.6 V, 9th – 1.2 V (THD 1.74%).

In figure 9, the result of the Burst Fire Control regulator's operation is presented. The third harmonic of the signal – 150 Hz, has an amplitude of 2.1 μV, 5th – 0.12 μV, 7th – 1.2 μV, 9th – 1.4 μV (THD 3μ%). These values are significantly smaller compared to the pulse angle method, which greatly simplifies, and in some cases, completely eliminates the need for reactive filters.

In figure 10, the result of the Pulse Width Modulation regulator's operation is presented. The third harmonic of the signal – 150 Hz, has an amplitude of 22.2 mV, 5th – 35.5 mV, 7th – 12.4 mV, 9th – 15.7 mV (THD 2.25%).

The above analysis indicates that the amplitude of the dominant harmonics does not change with variations in the electrical network voltage in the range of 217 V to 253 V RMS. From the conducted analysis, it can be inferred that among the discussed methods, the Burst Fire Control method is the best. This directly results from the fact that in this method, the load is always switched on for the full period. Analyzing only the 3rd harmonic, this method generates distortions that are 1000 times smaller than the PWM method. The Phase Angle Control method exhibits the worst parameters. The results of the harmonic distortion analysis for the remaining controller settings are presented in table 1.

The analysis indicates that the lowest harmonic distortions are generated by the Burst Fire Control controller. Regardless of the power regulation setting, the amplitude of the first 10 harmonics does not exceed 3 μV. In the case of the PWM controller, only in the case of 100% power setting does it exhibit slightly lower distortion levels than the others. This is due to its more complex control system compared to the other controllers and the ability to continuously activate the load. For the other settings, the amplitude of the first 10 harmonics does not exceed 40 mV.

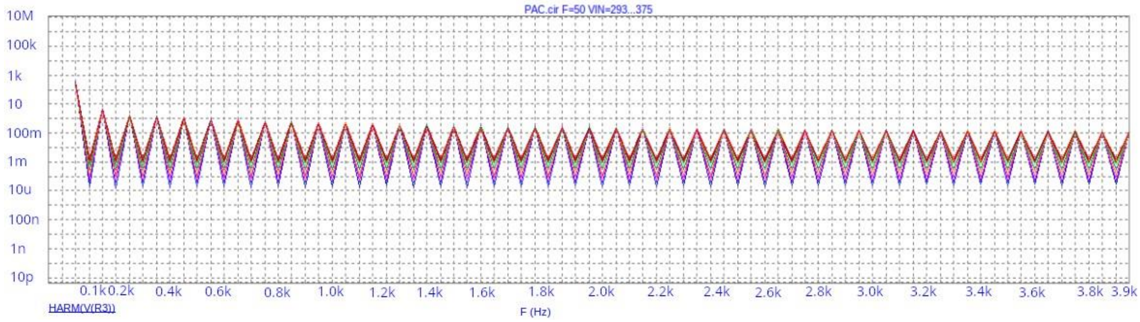


*Fig. 8. Harmonic distortion analysis for the Phase Angle Control regulator at 50% load power regulation and voltages ranging from 217V to 253V RMS*

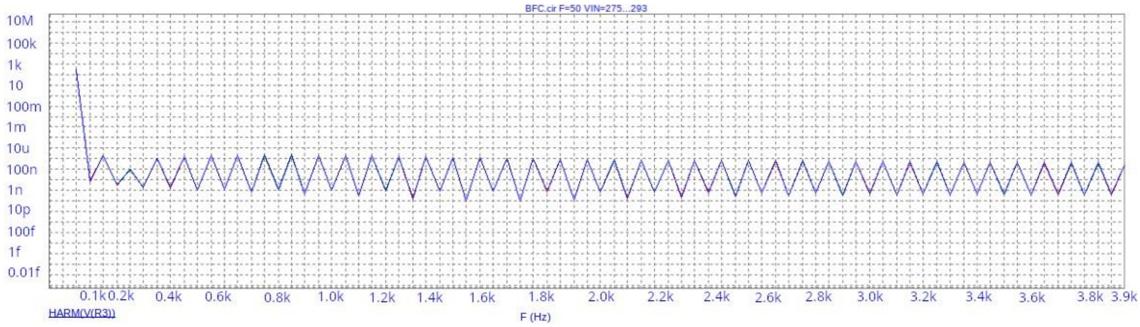


*Fig. 9. Harmonic distortion analysis for the Burst Fire Control regulator at 50% load power regulation and voltages ranging from 217V to 253V RMS*

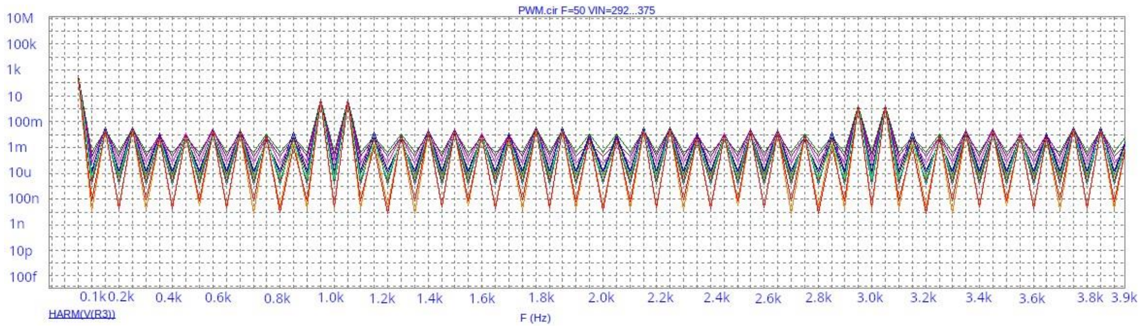


*Fig. 10. Harmonic distortion analysis for the PWM control regulator at 50% load power regulation and voltages ranging from 217V to 253V RMS*

*Table 1. Results of the harmonic distortion analysis for each of the discussed power regulation methods at load percentages of 25%, 50%, 75%, and 100%*

| Harmonic | 3th [V] | 5th [V] | 7th [V] | 9th [V] | max |
|---|---|---|---|---|---|
| **25%** | | | | | |
| Phase Angle Control | 4.59 | 2.2 | 1.2 | 1.04 | 3th – 4.6 V |
| Burst Fire Control | 2.1μ | 0.12μ | 1.2μ | 1.4μ | 3th – 2.1 μV |
| Pulse Width Modulation | 19.1m | 17.1m | 21.8m | 18.8m | 19th – 3.1 V |
| **50%** | | | | | |
| Phase Angle Control | 5.24 | 1.6 | 1.6 | 1.2 | 3th – 5.2 V |
| Burst Fire Control | 2.1μ | 0.12μ | 1.2μ | 1.4μ | 3th – 2.1 μV |
| Pulse Width Modulation | 22.2m | 35.3m | 12.4m | 15.7m | 19th – 3.5 V |
| **75%** | | | | | |
| Phase Angle Control | 2.3 | 2 | 1.2 | 0.64 | 3th – 2.3 V |
| Burst Fire Control | 2.1μ | 0.12μ | 1.2μ | 1.4μ | 3th – 2.1 μV |
| Pulse Width Modulation | 31.6m | 28.4m | 21.3m | 31.6m | 19th – 3.4 V |
| **100%** | | | | | |
| Phase Angle Control | 93m | 89m | 89m | 86m | 3th – 93 mV |
| Burst Fire Control | 2.1μ | 0.12μ | 1.2μ | 1.4μ | 3th – 2.1 μV |
| Pulse Width Modulation | 2.4μ | 0.4μ | 0.1μ | 0.1μ | 3th – 2.4 μV |

*Table 2. Results of the harmonic distortion analysis for each of the discussed power regulation methods at load percentages of 25%, 50%, 75%, and 100% after applying the EMI filter*

| Harmonic | 3th [V] | 5th [V] | 7th [V] | 9th [V] | max |
|---|---|---|---|---|---|
| **25%** | | | | | |
| Phase Angle Control | 191m | 32.1m | 6.44m | 2.26m | 3th – 191 mV |
| Burst Fire Control | 1μ | 0.01μ | 0.18μ | 0.26μ | 3th – 1 μV |
| Pulse Width Modulation | 551μ | 56.5μ | 38.3μ | 22.6μ | 19th – 42 mV |
| **50%** | | | | | |
| Phase Angle Control | 273m | 26.6m | 8.5m | 3m | 3th – 273 mV |
| Burst Fire Control | 1μ | 0.01μ | 0.18μ | 0.26μ | 3th – 1 μV |
| Pulse Width Modulation | 421μ | 68μ | 28μ | 21.8μ | 19th – 56 mV |
| **75%** | | | | | |
| Phase Angle Control | 174.1m | 28m | 6m | 2.1m | 3th – 174 mV |
| Burst Fire Control | 1μ | 0.01μ | 0.18μ | 0.26μ | 3th – 1 μV |
| Pulse Width Modulation | 395u | 64μ | 30μ | 10.7μ | 19th – 37 mV |
| **100%** | | | | | |
| Phase Angle Control | 2.8m | 0.68m | 0.27m | 0.13m | 3th – 2.8 mV |
| Burst Fire Control | 1.1μ | 0.01μ | 0.18μ | 0.26μ | 3th – 1 μV |
| Pulse Width Modulation | 1.4μ | 0.01μ | 0.01μ | 0.001μ | 3th – 1.4 μV |

On figure 11, the waveform of one cycle of the electrical power network voltage is presented for the pulse angle control method with the load set at 50% for voltages ranging from 217 V to 253 V RMS. Distortions with low-frequency characteristics can be observed. If the number of devices connected to the same phase is increased, the problem will exacerbate. In the case of the PWM method, as shown in figure 12, distortions appear evenly throughout the entire period, and their frequency depends solely on the switching frequency of the controller. This is an advantage of this control method. Moreover, with a greater number of devices operating at different frequencies, there should be no increase in the amplitude of the first harmonics of the electrical power network voltage.

Figure 13 shows the voltage waveform on one phase for the burst fire method. In the graph, you can observe the appearance of distortions with a much lower frequency than 50 Hz. These distortions result from the low-frequency switching of the switches in the controller. These disturbances can cause noticeable flickering of the lighting.

Table 2 presents the results of the analysis after applying an optional low-pass filter as shown in figures 3 and 6. The calculated inductance value for the PWM controller operating at a frequency of 1 kHz was 2.2 mH, and the capacitance was 50 μF. By increasing the operating frequency of the controller circuit to frequencies above 20 kHz (typically, controllers operate at frequencies greater than 30 kHz), the capacitance value can be reduced to 1 μF. For the Pulse Angle controller, the required capacitance value is 1 mF with an inductance of 10 mH.

The application of the filter reduced the amplitude of the first 10 harmonics by a factor of 100 to 1000 in the case of a PWM controller. In the case of the Pulse Angle method, the amplitude decreased 20–100 times. However, in the case of the Burst Fire Control method, the use of a low-pass EMI filter does not change the amplitude of harmonics appearing on the power grid side.

For low-frequency pulsations caused by the operation of the Burst Fire Control controller, the use of high-pass filters with a cut-off frequency of around 1 Hz is required, which may not be practical from a design and application perspective. In the case of the other two methods, the use of a filter significantly contributed to the reduction of harmonics.

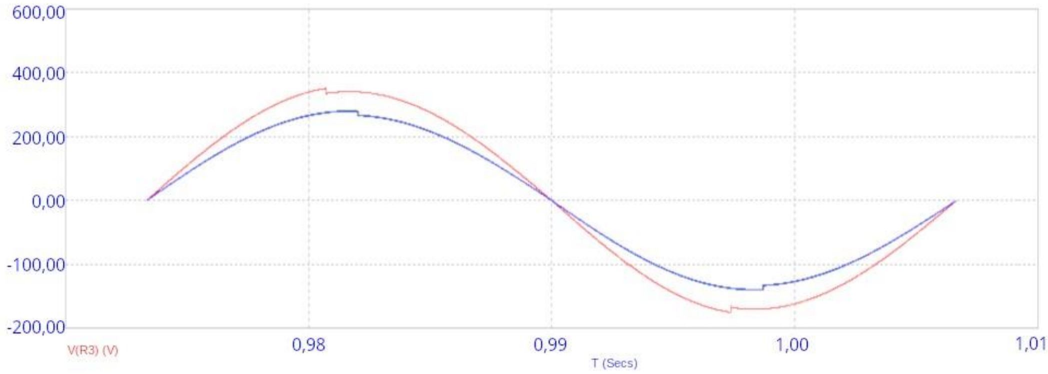


*Fig. 11. Waveform of one cycle of the electrical power network voltage for the pulse angle control method with the receiver's power set to 50%*

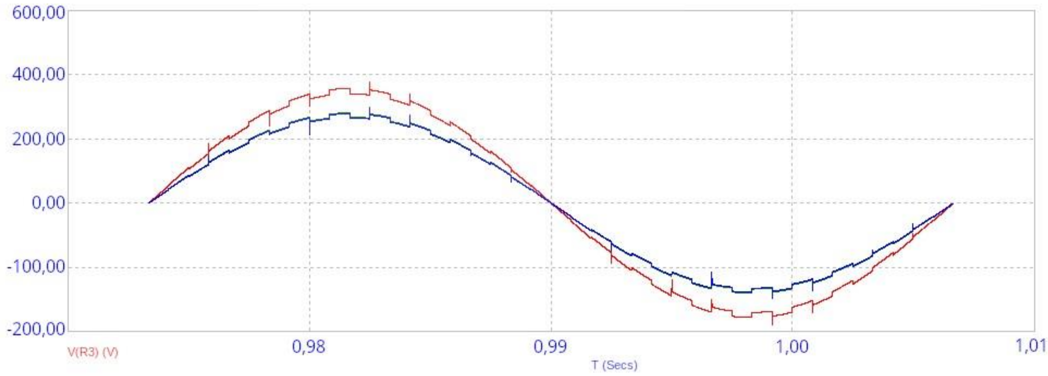


*Fig. 12. Waveform of one cycle of the electrical power network voltage for the PWM method with the receiver's power set to 50%*

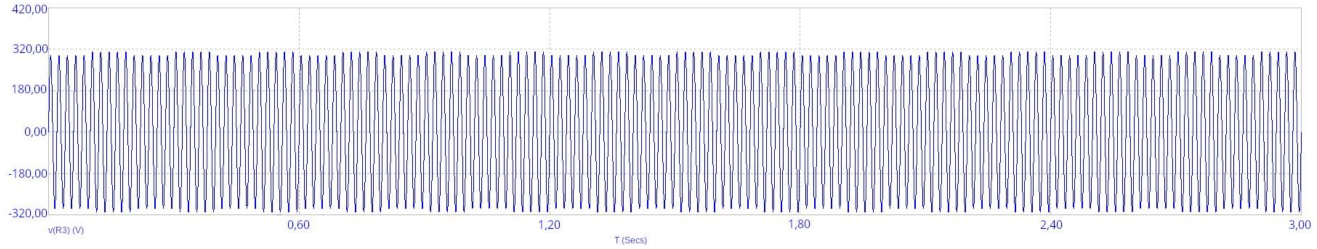


*Fig. 13. Voltage ripple of the electrical power network for the Burst Fire Control method with a 50% load*

## 4. Summary

The choice of the appropriate power regulation method for a receiver is crucial from the perspective of the power grid. The right method should not introduce additional distortions, and a proper control system will ensure that the voltage does not exceed permissible values. By using power regulation systems, it is possible to significantly increase energy self-consumption without drawing additional energy from the power grid.

For high-power systems, the PWM method appears to have the best parameters. After applying the appropriate filters, with significantly lower capacitance and inductance compared to other methods, the disturbances propagated to the power grid are the smallest among all the discussed techniques. Furthermore, by increasing the switching frequency of the switches, the size of the EMI filter can be reduced. This method also does not induce low-frequency pulsations, surpassing the Burst Fire Control method.

In summary, the PWM method has the best parameters for applications in power control of receivers operating in systems that increase energy self-consumption in photovoltaic systems.

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