

# Application Note

## AC-AC Automatic Voltage Regulator

### AN-CM-314

#### Abstract

*This app note presents a detailed description of the implementation of an AC-AC Automatic Voltage Regulator (AVR) using a GreenPAK SLG46537V CMIC. The purpose of AVRs is to maintain the voltage supplied to sensitive equipment within the predefined safe and functional limits of the device. For such applications, autotransformers are commonly employed providing different taps on windings which can be selected by electromechanical relays depending on the input voltages. A suitable controller is required to sense the input voltage and select a suitable tap to obtain the controlled output voltage. The low-cost SLG46537V CMIC is ideally suited for this purpose since it provides sufficient control circuitry to meet the requirements. The implementation of this CMIC as an AVR controller is thoroughly tested using appropriate experimentation, and the results verify the viability of the idea.*

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## AC-AC Automatic Voltage Regulator

### 1 Terms and Definitions

ASM	Asynchronous state machine
AT	Auto transformer
AVR	Automatic voltage regulator
BJT	Bipolar junction transistor
CMIC	Configurable mixed-signal integrated circuit
DO	Digital output
LUT	Look up table
MCU	Microcontroller unit

### 2 References

For related documents and software, please visit:

<https://www.dialog-semiconductor.com/products/greenpak>

Download our free **GreenPAK™** Designer software [1] to open the .gp files [2] and view the proposed circuit design. Use the **GreenPAK** development tools [3] to freeze the design into your own customized IC in a matter of minutes. Find out more in a complete library of application notes [4] featuring design examples as well as explanations of features and blocks within the GreenPAK IC.

- [1] [GreenPAK Designer Software](#), Software Download and User Guide
- [2] [AN-CM-314 AC-AC Automatic Voltage Regulator.gp](#), GreenPAK Design File
- [3] [GreenPAK Development Tools](#), GreenPAK Development Tools Webpage
- [4] [GreenPAK Application Notes](#), GreenPAK Application Notes Webpage

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## AC-AC Automatic Voltage Regulator

### 3 Introduction

Automatic Voltage Regulators (AVRs) are used to regulate a supplied voltage level by compensating for any fluctuations in the incoming voltages. AVRs are also commonly known as voltage stabilizers and have applications in many industrial and residential applications. For example, AVRs are used in generator sets on ships, in emergency power supplies, and on oil rigs to stabilize voltage levels during fluctuations in power demand.

For power utility companies, voltage regulation in the distribution network is a key responsibility determining the power quality delivered to end consumers. To this end, utility companies must ensure proper short and long term planning, maintenance of the power equipment, and deployment of regulators on distribution lines. However, this may be a challenging task, especially in some regions of the world. In many South Asian countries, including Pakistan, India, and Bangladesh, the power distribution system is fragile due to issues of power theft and a dearth of power generation, which can lead to periods of load shedding and other disruptions. As a result, end users can face issues of power line voltage fluctuations. Therefore, to ensure the safety and proper functionality of expensive devices like air conditioners, refrigerators, and televisions, the use of small portable AVRs is very popular. AVRs are easy to use devices that generally operate in a predefined range of voltage levels (e.g. 150 – 240 V or 90 – 280 V).

Functionally, AVRs generally use a tapped autotransformer to maintain the AC output in an acceptable range. A feedback mechanism is employed to control the position of the taps by switching appropriate relays to regulate the output voltage. This usually consists of two units: a sensing unit and a regulating unit. The job of the sensing unit is to determine the input and output voltage levels of the stabilizer, whereas the regulating unit keeps the output voltage in acceptable predetermined limits.

Traditionally, op amp ICs are used in conjunction with analog comparators for control in relay-based AVR designs. More recently, the use of 8-bit microcontrollers (MCUs) has significantly increased in digitally controlled commercially available AVRs. However, similar functionality and features can be achieved using low-cost GreenPAK. This replacement can be advantageous in terms of reduced cost and space requirements, and no need to explicitly program an MCU.

In this application note, we explain how a SLG46537V can be used to develop an AVR. The overall system design and the GPAK design will be thoroughly described. To validate the feasibility and operability of this AVR, we also present the experimental results obtained from a prototype.

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### 4 System Design

#### 4.1 Block Diagram

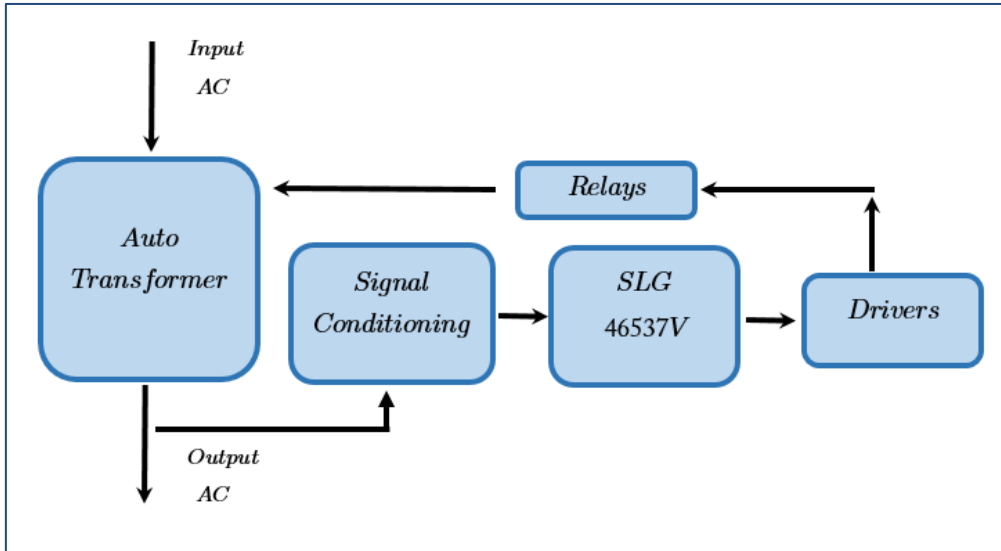


Figure 1: Block Diagram

The functional block diagram of the proposed AVR design is shown in Figure 1. The system is essentially based on a feedback mechanism. The AC voltage at the output of the AVR is conditioned to reduce it to the functional DC limits of the SLG46537V CMIC. Depending on the sensed voltage, appropriate relays are driven by the CMIC to select the suitable tap windings on the autotransformer.

#### 4.2 Specifications

The specifications of an AVR depend on the particular application. In this app note, our AVR has the following specifications:

- The input voltage ranges from 125 V to 240 V.
- The output voltage is regulated between 200 V and 240 V.
- Undervoltage and overvoltage protection features are provided. When the AVR output voltage falls below 180 V (undervoltage) or rises above 255 V (overvoltage), the output supply is disconnected.
- Four electromechanical relays are used in the AVR design.
- An autotransformer is used for voltage step-up which has a 0 V neutral connection and four additional taps at 135 V, 174 V, 196 V and 220 V.
- The output waveform and frequency are unchanged from the input.
- The AVR (controller) design is inexpensive.
- LED indicators are used to signal normal, overvoltage, or undervoltage conditions.

Note that these specifications are arbitrary. The given specifications can easily be adjusted in the configuration of the CMIC depending on the actual application.

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4.3 Functional Design

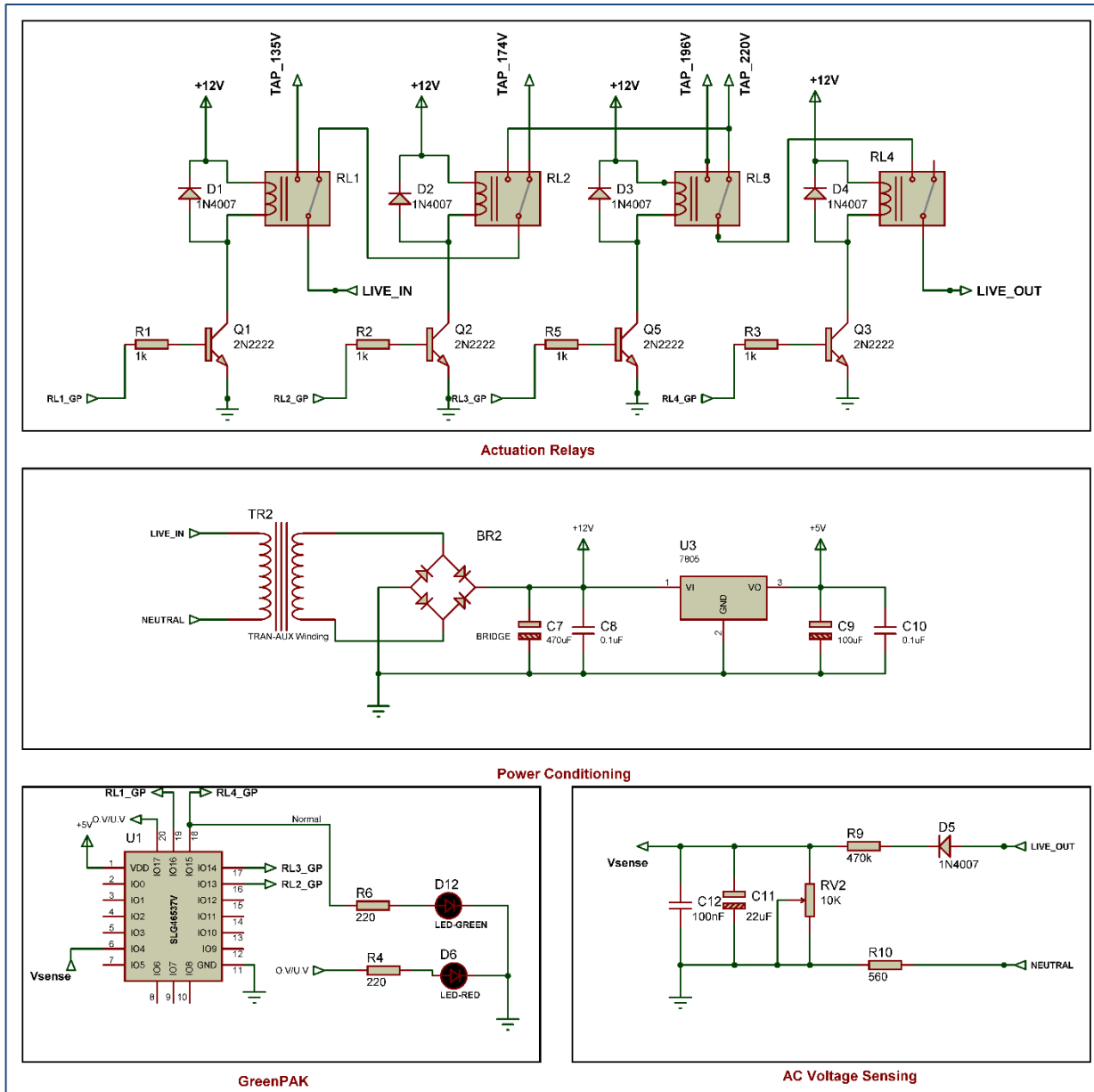


Figure 2: Proposed AVR Design

Figure 2 shows the proposed functional design of the AVR using the SLG46537V CMIC.

Power Conditioning

The power conditioning block powers the GreenPAK CMIC. It takes the live AC as input and steps it down to 12 V, which is further converted to 5 VDC using a suitable voltage regulator IC.

AC Voltage Sensing

For voltage sensing, the output AC voltage (**Live\_out**) is stepped down and rectified to obtain a low voltage DC level using a diode and resistive divider network. Subsequently, an output filter (electrolytic capacitor) is used to minimize the ripple and obtain a constant smooth DC voltage. A bypass capacitor is also employed to filter out the transients. Hence, a filtered DC voltage (**Vsense**) is obtained. To ensure the DC voltage levels are compatible with the CMIC, a step-down factor of (approximately) 0.01 was used (i.e. 200 VAC  $\leftrightarrow$  2 VDC).

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### GreenPAK

Using **Vsense** and based on GreenPAK logic (Section 5), the CMIC drives the required relays (through BJTs) for actuation. Digital outputs from the CMIC are also used to toggle LED indicators to inform the user about the normal and over/undervoltage conditions of the AVR. The schematics of the CMIC, showing the IO connections, have been provided for reference.

### Actuation

Three electromechanical relays (RL1, RL2, and RL3) are employed to switch the input AC voltage (**Live\_in**) connection between the 135 V, 174 V, 196 V and 220 V taps of the autotransformer. A fourth electromechanical relay (RL4) is used to disconnect the AVR output in case of undervoltage or overvoltage conditions, thus preventing any damage to the attached load at the AVR output.

## 5 GreenPAK Logic

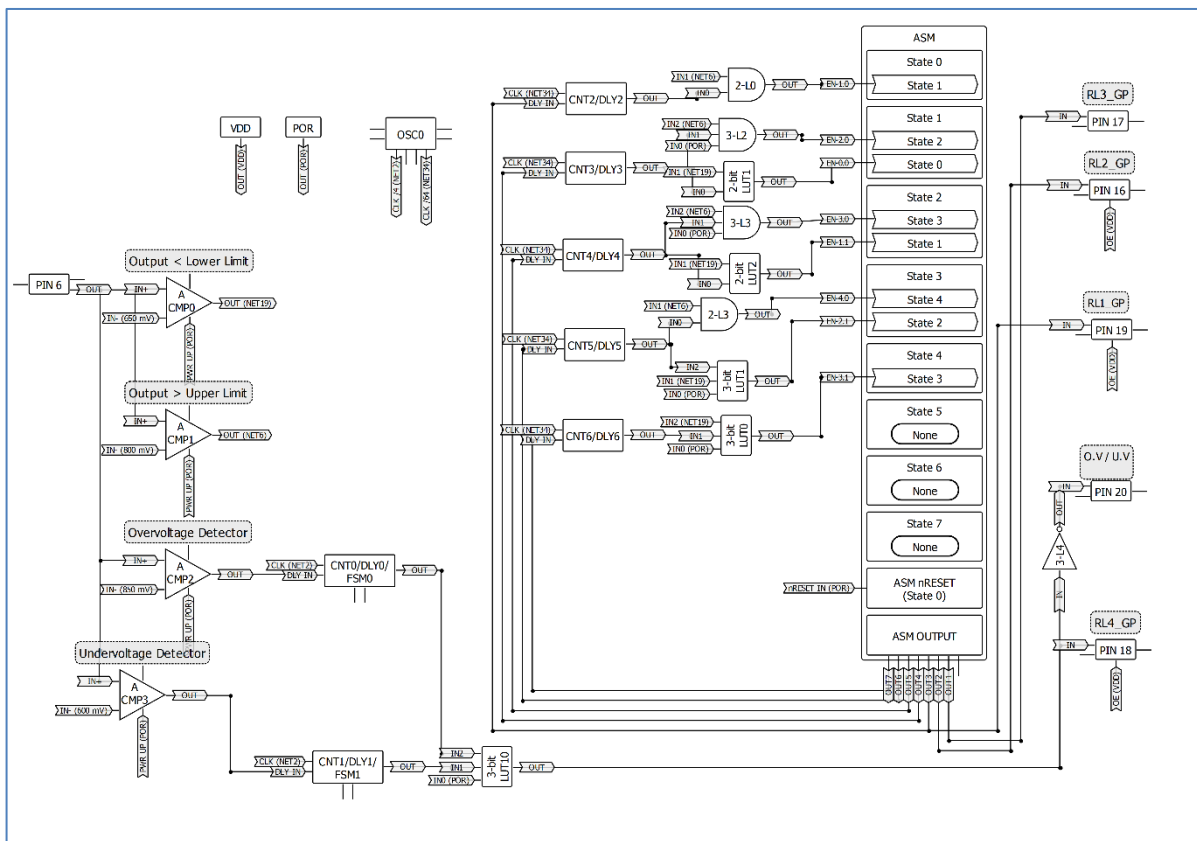


Figure 3: GreenPAK Design Schematic

Figure 3 shows the schematic of the GreenPAK design. **Vsense** is fed to different comparators using Pin 6. Analog comparators ACMP0 and ACMP1 are used for regulation in the normal working range of the AVR, whereas ACMP2 and ACMP3 are used for overvoltage and undervoltage detection. Since the maximum internal reference of the comparators can be set no greater than 1.2 V, a gain of 0.33 is used to ensure the output voltage can be compared and correctly categorized in different ranges. The references of the comparators are set to meet the specifications outlined in Section 4.2. An asynchronous state machine (ASM) block is employed to set up a finite state machine for voltage regulation.

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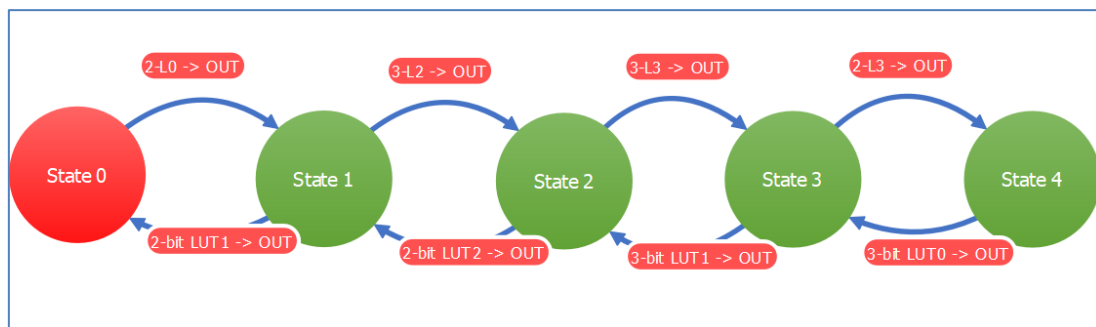


Figure 4: Finite State Machine

Figure 4 depicts the five states that are used. In each state relays 1, 2, and 3 are actuated using the ASM outputs OUT3, OUT2 and OUT1 respectively. This enables the selection of the relevant autotransformer taps and consequently the autotransformer turn ratio. Moving from State 0 to 4 causes a stepwise decrease in the autotransformer turns ratio. Table 1 shows the correspondence of each state to the turns ratios.

Table 1: AT Turn Ratios Corresponding to Each State

State	0	1	2	3	4
AT turn ratio	220/135 ≈ 1.63	196/135 ≈ 1.45	220/174 ≈ 1.26	196/174 ≈ 1.13	220/220 = 1

Voltage regulation is achieved using state transition which occurs if **Live\_out** is greater than the upper limit (≈ 240 VAC, set by reference of ACMP1) or less than the lower limit (≈ 200 VAC, set by reference of ACMP0). If any state does not produce the desired regulated output voltage level (200 V < **Live\_out** < 240 V), a state change (autotransformer turns ratio) takes place. In particular, if **Live\_out** is greater than the upper limit, a transition to a higher state takes place. Transitions to a higher state (lowering of autotransformer turns ratio) continue until the desired voltage level is achieved. Similarly, for **Live\_out** less than the lower limit, a transition to a lower state occurs.

To ensure that electromechanical relays function properly, abrupt state transitions are controlled by using delays in the feedback of the ASM block. To this end, outputs of the ASM block OUT3, OUT4, OUT5, OUT6, and OUT7 are fed to the delay blocks DLY2, DLY3, DLY4, DLY5, and DLY6, respectively. Figure 5 depicts the configuration of the RAM block of the ASM, where the status of each of the binary outputs OUT0 – OUT7 is shown.

State name	Connection Matrix Output RAM							
	OUT7	OUT6	OUT5	OUT4	OUT3	OUT2	OUT1	OUT0
State 0	0	0	0	0	1	0	0	0
State 1	0	0	0	1	1	0	1	0
State 2	0	0	1	0	0	0	0	0
State 3	0	1	0	0	0	0	1	0
State 4	1	0	0	0	0	1	0	0
State 5	0	0	0	0	0	0	0	0
State 6	0	0	0	0	0	0	0	0
State 7	0	0	0	0	0	0	0	0

Figure 5: RAM Block

States are retained for a predefined timed period  $t_p$  (≈ 0.5 s) set in the delays. State transitions occur only if **Live\_out** remains out of the desired range for at least  $t_p$ . Outputs of the delays are fed back to different LUTs (and AND blocks) along with outputs of ACMP0 and ACMP1, as shown in Figure 4.



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This ensures that state transitions only occur once  $t_p$  elapses and **Live\_out** is out of the desired range. The particular state transition depends on the outputs of ACMP0 and ACMP1. For example, if State 1 is retained for  $t_p$ , no transition is possible to State 0 and State 2. If the desired voltage level has been reached, State 1 is maintained. Otherwise, a transition to State 0 and State 2 occurs depending on whether **Live\_out** is greater than the upper limit or less than the lower limit.

Another important feature of the proposed GreenPAK design is protection during overvoltage and undervoltage conditions. Comparators ACMP2 and ACMP3 are used for overvoltage and undervoltage conditions respectively. The output of the ACMP2 and the inverted output of ACMP3 are passed to the delay blocks DLY0 and DLY1 to ensure that overvoltage and undervoltage conditions are not detected for any transients. Subsequently, the outputs of DLY0 and DLY1 are fed to an LUT block which decides if it is a normal, overvoltage, or undervoltage condition. Under normal conditions, RLY4 is kept energized and the AVR regulates the voltage. Otherwise, no regulation is possible and RLY4 trips. Indications for the normal, overvoltage, and undervoltage conditions are also provided for the user.

## 6 Experimental Results

### Experimental Hardware

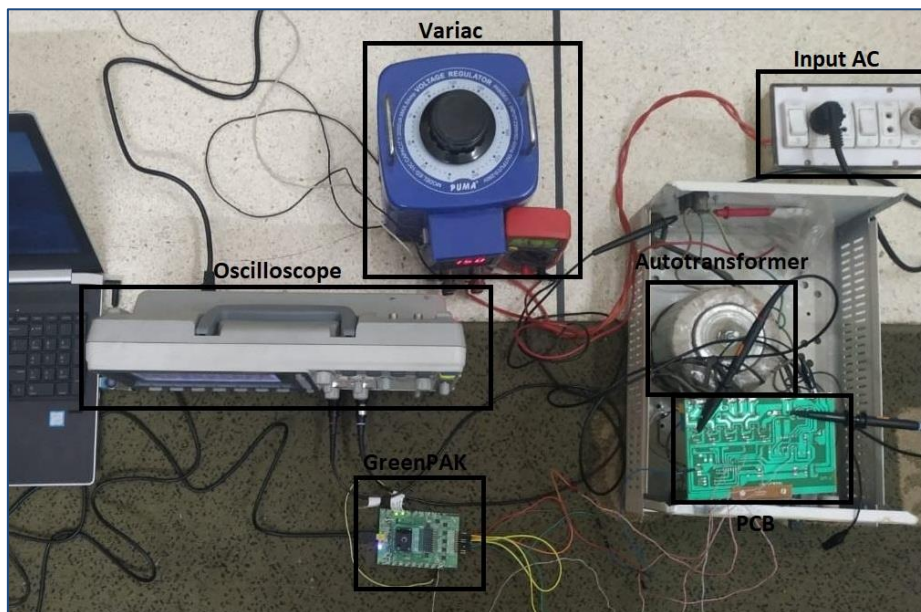


Figure 6: Experimental Setup

Figure 6 shows the experimental setup for the prototype. A Variac is used to control the input AC voltage supplied to the AVR. The AVR contains an autotransformer and a PCB which contains the control circuitry. A GreenPAK development board is connected to the PCB to control the electromechanical relays. An oscilloscope is used to log the input and output voltages.

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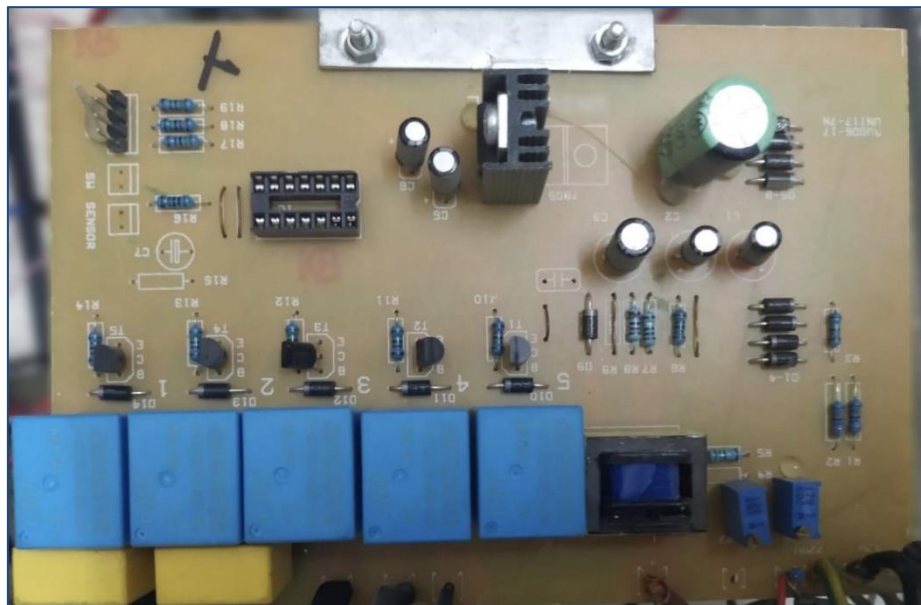


Figure 7: PCB Circuitry

Figure 7 shows the PCB circuitry where the electromechanical relays, BJTs, and other auxiliary components are mounted.

Oscilloscope Results

The following figures show the oscilloscope logs for the experimentation. The yellow and blue markers show the input and output voltages respectively.

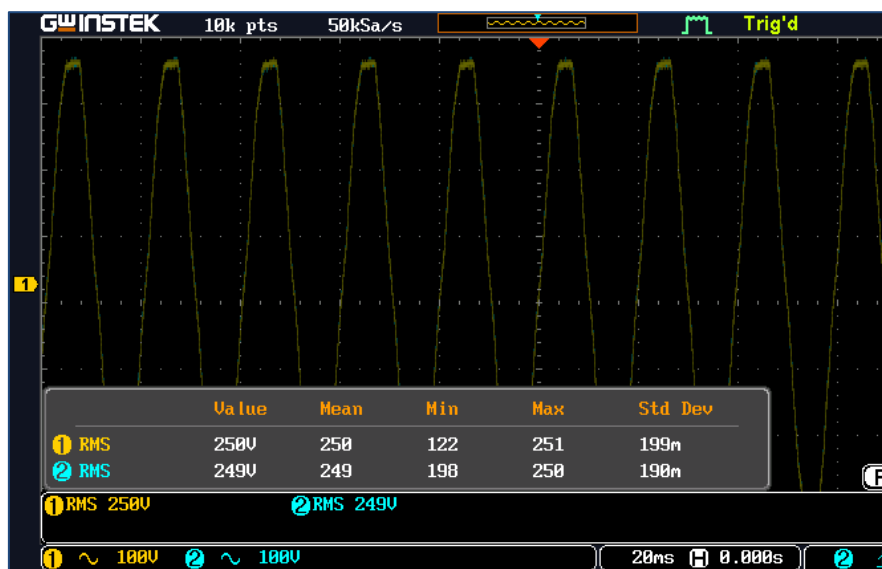


Figure 8: Quantitative Experimental Summary

Figure 8 depicts the quantitative summary of the experimental results for the normal functionality of the AVR. The input voltage is swept in a voltage range (low to high) and the corresponding output voltage is observed. The CMIC successfully drives the relays to change the autotransformer taps and hence the turns ratio from 1.63 to 1 for voltage regulation.

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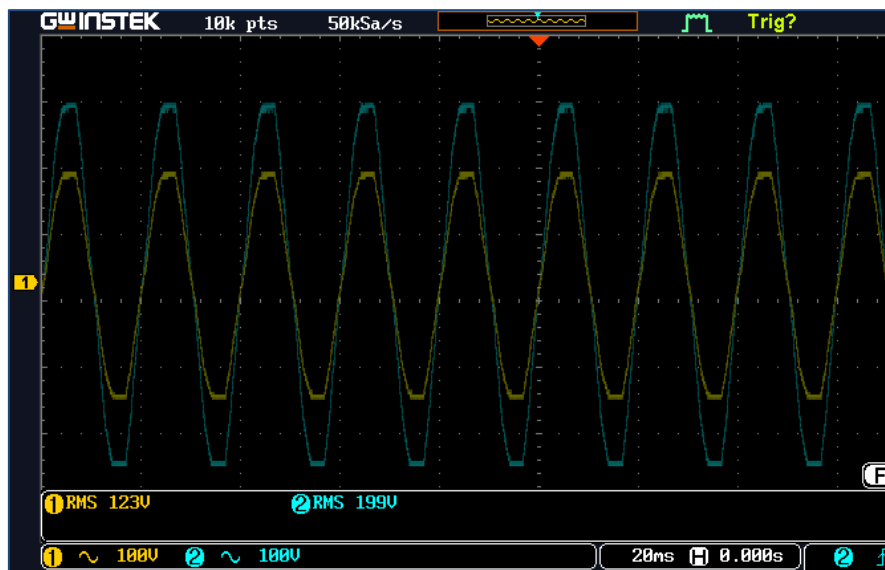


Figure 9: Normal Functionality

Figure 9 shows the normal functionality of the AVR where the tap for turns ratio of 1.63 is successfully determined and selected.

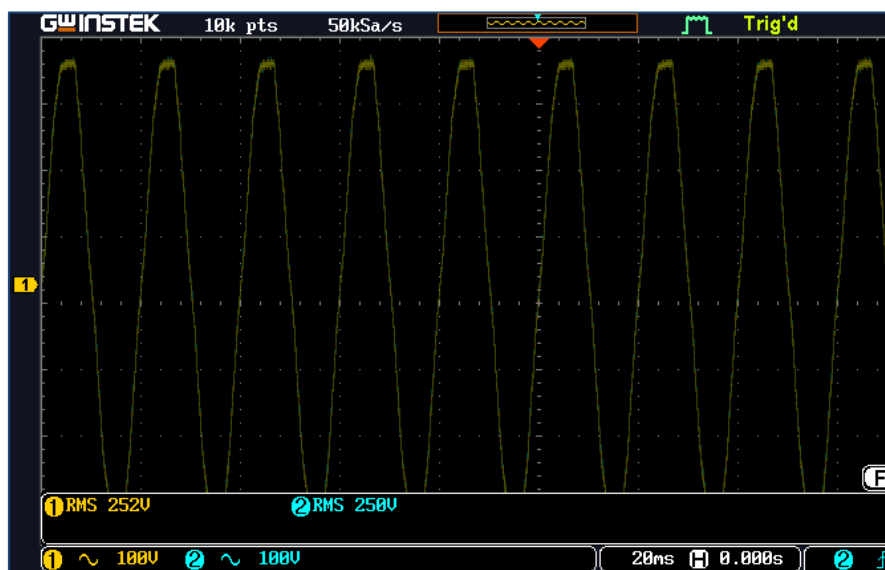


Figure 10: Approaching Overvoltage

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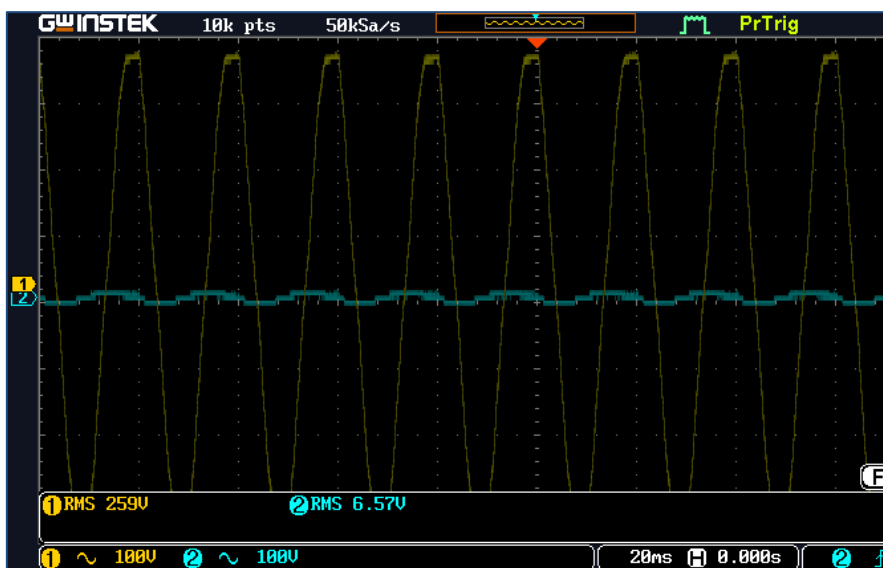


Figure 11: Overvoltage Condition

Figure 10 depicts the input and output voltages waveforms when the overvoltage condition is approaching. Both have similar waveforms as the tap for turns ratio is 1.

Figure 11 shows the case of the over-voltage condition. It can be seen that the output voltage has collapsed as the AVR has successfully tripped RL4 for protection.

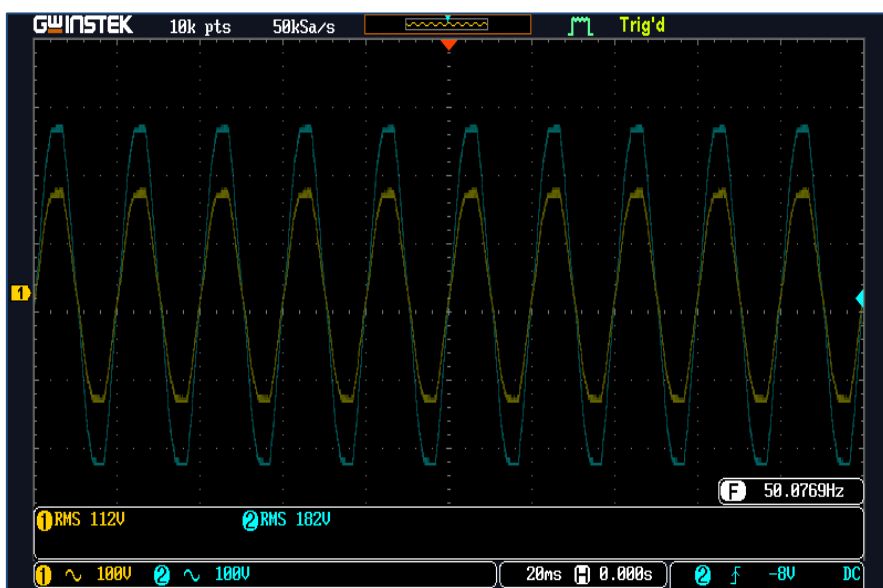
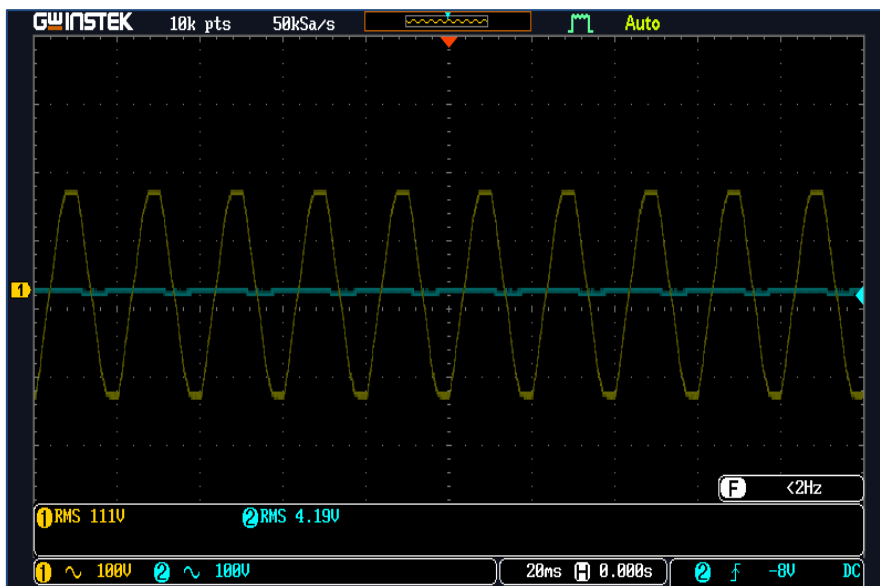


Figure 12: Approaching Undervoltage

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**Figure 13: Undervoltage Condition**

Figure 12 depicts the input and output voltage waveforms when the undervoltage condition is approaching. The AVR selects the tap for maximum turns ratio (1.63) under this condition.

Figure 13 shows the case of the undervoltage condition. It can be observed that the output voltage falls as RL4 has been tripped for protection.

Note that there is no frequency change or phase shift of the input and output voltages when the AVR is regulating.

## 7 Conclusions

This app note described the use of the GreenPAK SLG46537V CMIC as a controller for AVRs, which are popular in residential and industrial applications. The CMIC can replace discrete components and MCUs that are currently used in these applications. The role of the SLG46537V in the proposed AVR was illustrated and the GreenPAK design was explained thoroughly. Moreover, the details of experiments on a prototype AVR were presented to validate the proposed design. We conclude that the SLG46537V provides ample capabilities to serve as a controller, particularly in residential AVRs. Hence, control units for AVRs can be designed using the SLG46537V that are inexpensive and reduce the PCB footprint. More sophisticated controllers can be designed using other GreenPAK ICs, especially those offering ASMs with more states.

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**AC-AC Automatic Voltage Regulator**

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**Revision History**

<b>Revision</b>	<b>Date</b>	<b>Description</b>
1.0	23-Jun-2021	Initial version.

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### Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,  
Koto-ku, Tokyo 135-0061, Japan  
[www.renesas.com](http://www.renesas.com)

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