# Design and Implementation of Rapid Shutdown Filters for Roof Integrated Photovoltaic Cells

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***Abstract*** **- Rapid shutdown for rooftop PV cells requiresan inside array boundary of 305mm to be de-energized to 30 Volts or less within 30 seconds of initiation of a rapid shutdown event, according to Sunspec specifications. The specification set by Sunspec allows controllers to communicate using a single communication protocol defined by Sunspec, providing interoperability between different components, which utilizes power-line (PLC) communicationas a mean of transferring data. This paper proposes a systemarchitecture for a rapid shutdown receiver, that utilizes multi-stage feedback band-pass filtering techniques to actively remove noise from the PLC network and deliver the S- FSK message transmitted to the decision-making block with frequencies to the Mark and Space of frequencies 131.25kHzand 143.75kHz respectively. Furthermore, this paper uses a signal mixing technique to enhance the system's reliability, stability, and provides another layer of security via utilizing the low-frequency as an enabling signal to the decision- making stage (not covered in this paper).**

***Keywords - Power-Line Communication (PLC), Spread Frequency Shift Keying (S-FSK), Photovoltaic (PV), Rapid Shutdown System (RSD), Sunspec, Multi-Stage Band-Pass Fil-tering, National Electric Code (NEC), National Fire ProtectionAssociation (NFPA)***

## I. INTRODUCTION

Similar to the world's population growth, renewable energy source is also growing exponentially, with holding a strong 23.9% of the energy generation as of 2019. The National Electrical Code (NEC) and Sunspec introduced strict requirements for the communication signal specification to effectively de-energize solar PV panels, on a modular level. Paper [1] introduced the specificationobjectives of a typical Rapid Shutdown system, according to Sunspec specification, for the purpose of describing an open communication framework.

TABLE I. RAPID SHUTDOWN SYSTEM REQUIREMENTS

| Transmitter Specification | min. | Nom. | Max. |
|---|---|---|---|
| Mark Frequency (kHz) | 131.236875 | 131.25 | 131.263125 |
| Space Frequency (kHz) | 143.735625 | 143.75 | 143.764375 |
| Average Bit Period (ms) | 5.119488 | 5.12 | 5.120512 |
| Transmission Period (ms) | 168.943104 | 168.96 | 16.976896 |
| Quiet Period (ms) | 901.029888 | 901.12 | 901.210112 |
| Cycle Period (ms) | 1,069.972992 | 1,070.08 | 1,070.187008 |

Sunspec introduced a PLC protocol to transfer data from the transmitter to the receiver, where the transmitter continuously transmit amark and space, using barker 11-bit Code as a modulationsignal, transmitted via S-FSK carrier signal with the mark and space frequencies of 131.25kHz and 143.75kHz respectively, with bit duration rate of 5.12ms, transmission period of 168.96ms, quiet period of 901.12ms, and cycle completion period of 1,070.08ms, all transmitted via the power-line cable, as shown in Table I.

## II. LITERATURE REVIEW AND LIMITATIONS OF CURRENT TECHNIQUES

Rapid shutdown requirements came into effect as of January 1st, 2019, in which several companies had presented their solutions in attempt to comply with the NEC 2017 code, and Sunspec standards [8], however, several companies were not able to comply with the said standards. As an example, Ginlog Receiver's [9] attempt on a RSD system complies with the National Code NEC 2014, however, were not able to meet the Sunspec communication protocol described in Paper [1]. SMA's RSD System [11] is an example of a compliant receiver with both NEC 2017 and Sunspec standards and protocols, in which the signal generated and transmitted by the transmitter was successfully demodulated through the PLC System, and is able to effectively de-energize the system as per Sunspecs protocol and standards.

This paper presents the design technique by utilizing multi-stage feedback band-pass filtering to meet and exceed the protocol requirement set by Sunspec [8]

The following section presents the Out-Band and In-Band filtering, mixing techniques that grants further security andstability to the overall system.

## III. PROPOSED FRONT END SYSTEM ARCHITECTURE

Figure 1 shows the proposed Rapid shutdown system architecture, which consists of 5 main system blocks, such that:

Block 1: Power Line Communication (PLC) coupling and initial filtering stage
Block 2: Out-band and In-Band Filters
Block 3: Oscillator Stage
Block 4: High Pass filter
Block 5: Enabling Stage
Block 6: Central Processing Unit.

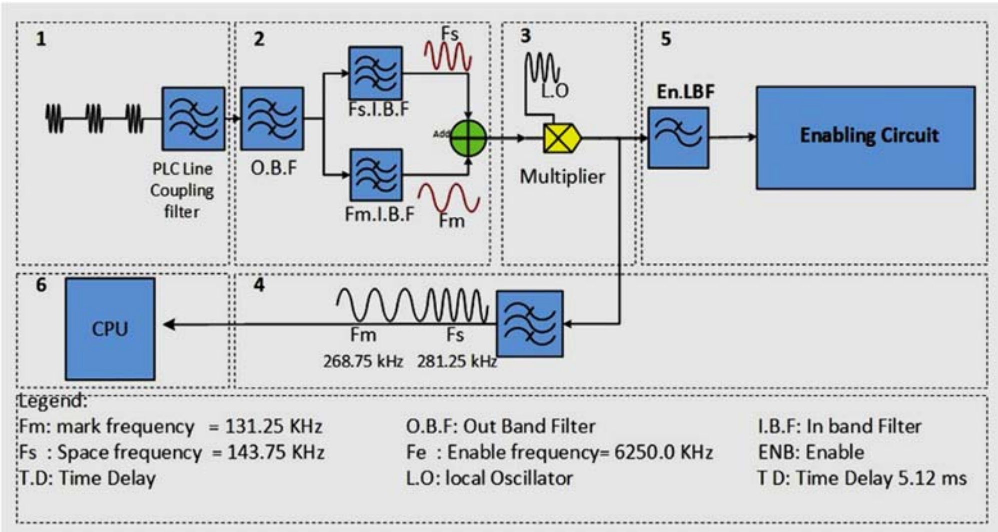


Fig. 1. Proposed rapid shutdown system architecture

### *A. Block 1: PLC Line Coupling and Initial Filtering Stage*

Coupling the PLC line to the receiver requires an High Voltage (HV) capacitor with a rating of $1kV_{DC}$, as well asa PLC coupling transformer to allow the S-FSK message to be sent to the receiver, ensuring an elimination of anyline spikes, and creating an AC path for the signal, while blocking any DC voltages.

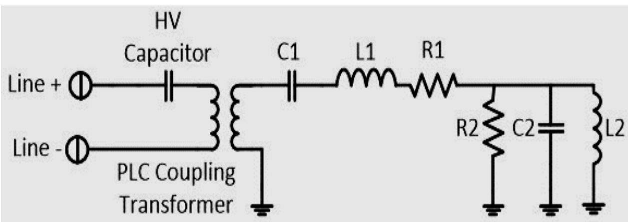


Fig. 2. PLC coupling and filtering stage

Figure 2 shows the design of the PLC Filter to have a center frequency of 137.5kHz, and a -3dB bandwidth of 160kHz. The filter was simulated on LTSpice, and with the frequency response indicated in Figure 3.

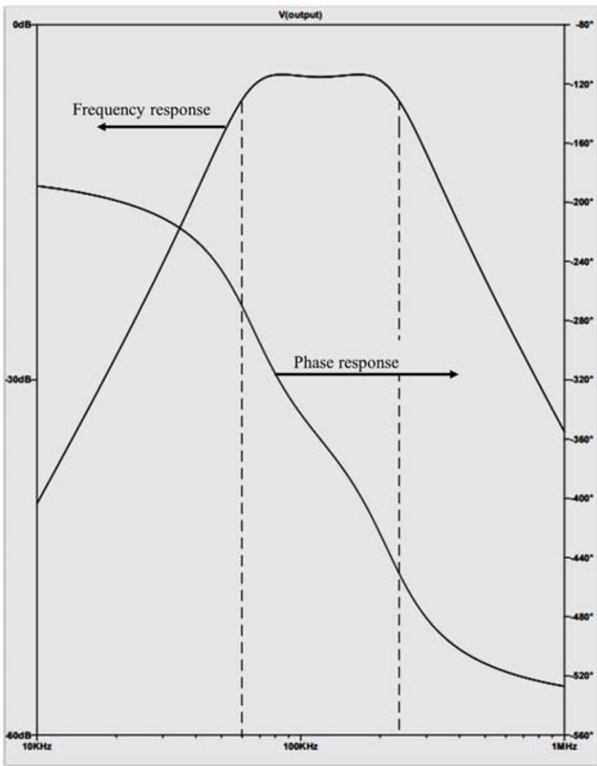


Fig. 3. PLC filtering response

*B. Out-Band and In-Band Filters*

In order to achieve SunSpec's specification, a multi-feedback band-pass active filter shown in figure 4 configuration was used, with a transfer function of:

$$T(s) = -\frac{SC/R_1}{S^2C^2 + 2SC/R_2 + 1/R_1R_2} \tag{1}$$

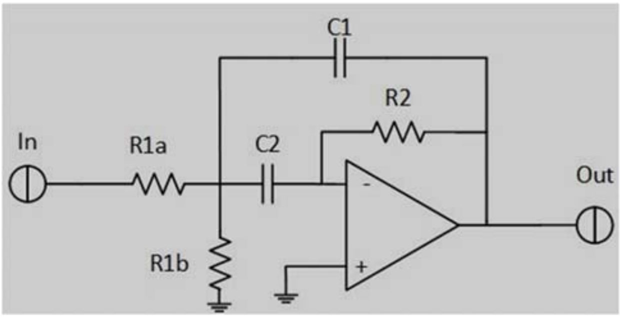


Fig. 4. Multi-feedback band pass active filter

If the coefficients of the transfer functions equate with the general transfer function of the above equation, the following expression is derived for the element values:

$$R2 = Q/(\pi f_r C) \tag{2}$$

$$R1 = R2/(4Q^2) \tag{3}$$

The Q-factor is the reciprocal of the fractional bandwidth, the higher the Q, the narrower the passband, and vice- versa. The voltage gain at resonant frequency (Ar) can be obtained from the following equation:

$$Ar = 2Q2 \tag{4}$$

The resistors $R1_a$ and $R1_b$ form a voltage divider so that the overall gain of the circuit could be controlled. The parallel combination of the two resistors equal to R1 in order to retain the resonant frequency. The section gain (Ao), which is the gain of a single band-pass section at the filter geometric center frequency $f_o$ is given in the equation 8. Thus, the transfer function of the system could be modified to the following equation 5. Table IV on page 5 shows the full specification requirements for the in-band and out-band filters required for the rapid shutdown system. The closed-loop out-band, mark, and space filters' responses are shown in figures 5, figure 6, and figure 7, respectively.[2]

$$T(s) = -\frac{SR_2C}{S^2R1_aR_2C^2 + 2SR1_aC + (1 + \frac{R1_a}{R1_b})} \tag{5}$$

$$R1a = R2/2Ar \tag{6}$$

$$R1_b = (R_2/2)/(2Q^2 - A_r) \tag{7}$$

$$A_o = \frac{A_r}{\sqrt{1 + \left(\frac{2Q\Delta f}{f_r}\right)^2}} \tag{8}$$

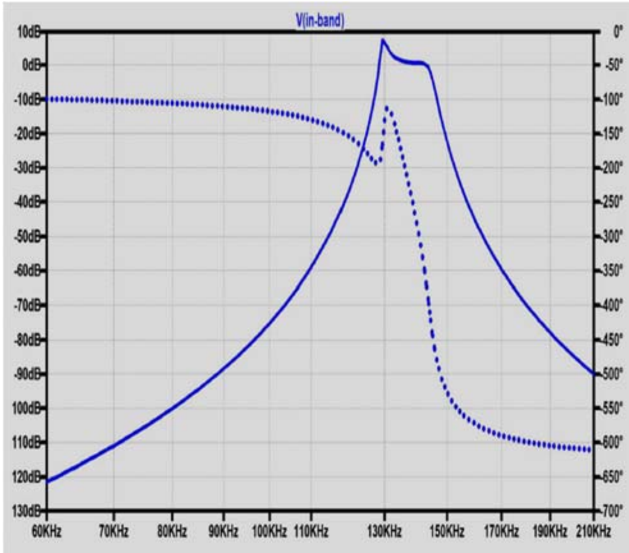


Fig. 5. Outband filter response

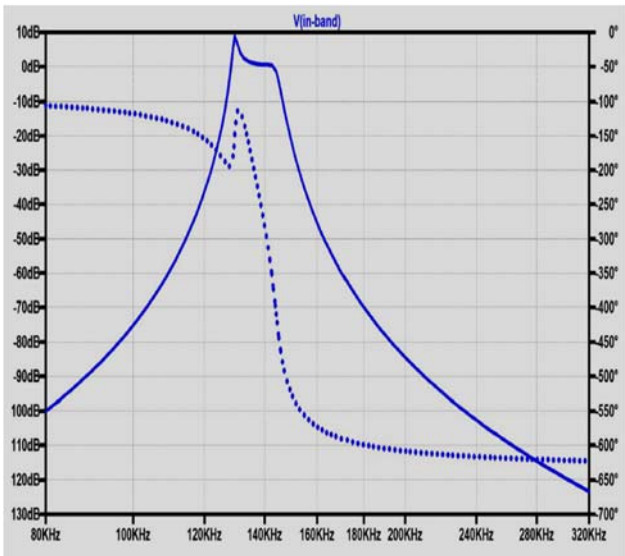


Fig. 6. Mark filter response

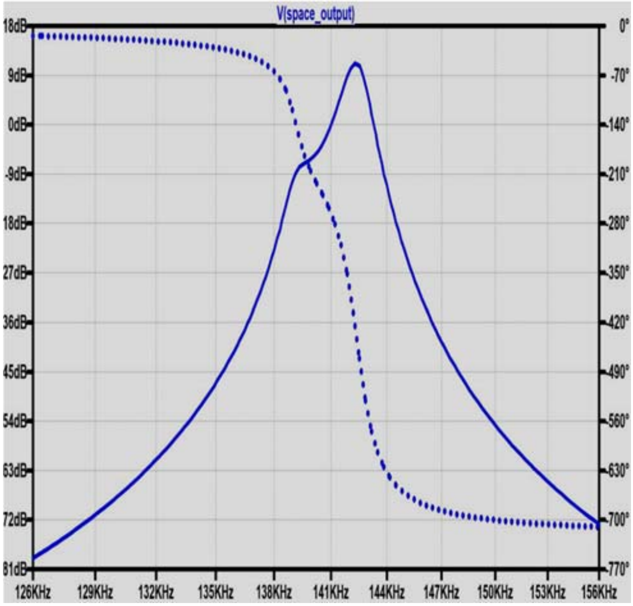


Fig. 7. Space filter response

### C. Oscillator Stage

The output of the band-pass filter stage is multiplied by the central frequency of 137.5kHz, outputting the enabling frequency of 6.25 kHz, as well as the respective high frequencies of the mark and space for further processing.

At the output of the in-band filters we have two signals either a mark or space at a time, multiplying those signals with a center frequency of 137.500 kHz, the output of this multiplication is two component: high component and low component for each mark and space frequency, as shown in the figure 7. The results are shown in Table II, and the spectrum is represented in Figure 8.

$$2sin(\alpha)cos(\beta) = sin(\alpha + \beta) + cos(\alpha - \beta)$$

TABLE II. OSCILLATOR STAGE SIGNAL MIXING

| Signal #1 | | Signal #2 | | | Output Signal | |
|---|---|---|---|---|---|---|
| Oscillator | | Mark/Space | | | High Freq. | Low Freq |
| 2 cos | 137,500 | sin | 131,250 | = | 268,750 | 6,250 |
| 2 sin | 137,500 | sin | 131,250 | = | 268,750 | 6,250 |
| 2 cos | 137,500 | cos | 131,250 | = | 268,750 | 6,250 |
| 2 cos | 137,500 | sin | 143,750 | = | 281,250 | 6,250 |
| 2 sin | 137,500 | sin | 143,750 | = | 281,250 | 6,250 |
| 2 cos | 137,500 | cos | 143,750 | = | 281,250 | 6,250 |

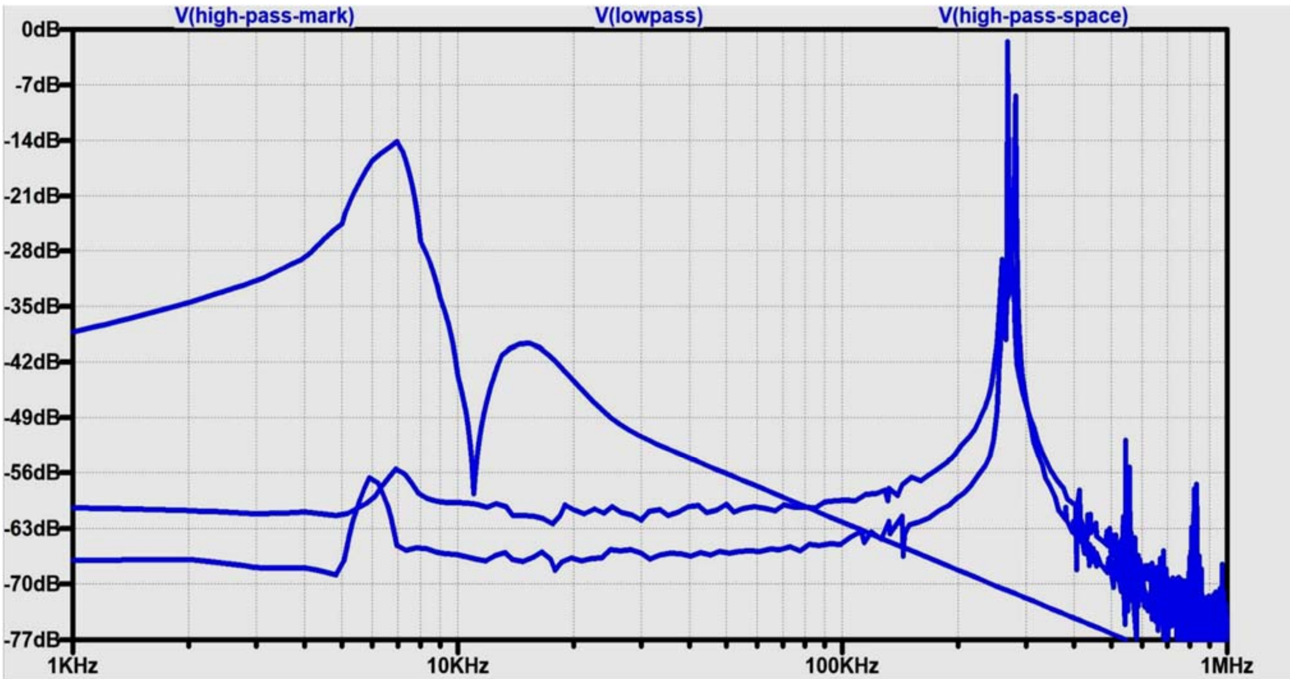


Fig. 8. Mixer output response

Once the system is enabled the shifted frequencies [268.750 kHz] and the [281.25 kHz] which represents the mark and space receptively are passed to the following stages for further processing.

## IV. EXPERIMENTAL METHODOLOGY

The system must undergo several test described by Sunspec, one of which is the in-band and out-band interference rejection, where an interference signal is sent with a varying frequencies between 30kHz and 500kHz, according to figure 9 of Sunspec [5]. The receiver must be able to be immune to any single-tone blocking signalto the right or left of the space or mark frequencies.

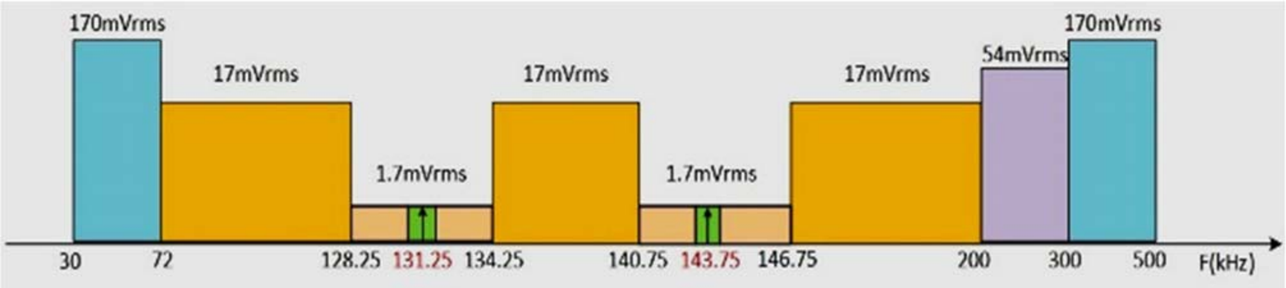


Fig. 9. Signal interference test

## V. RESULTS AND DISCUSSIONS

The system was tested against the edges (critical points), using LTSpice Simulation software, and the results are depicted in Table III, indicating that the filters were able to attenuate the single interferer tones effectively and comply with the requirements of Sunspec.

Table IV shows the filter design specifications and calculations.

* Reference to the carrier signal with amplitude 1.7mV, as per Sunspec.

TABLE III. SIGNAL TESTING AND OUTPUT

| F (Hz) | V (mV) | dBc* | Stage | Obtained dBc | Signal Test |
|---|---|---|---|---|---|
| 30,000 | 170 | -40 | Out-band | -158 | Pass |
| 70,000 | 170 | -40 | Out-band | -109 | Pass |
| 121,250 | 17 | -20 | Out-band | -30 | Pass |
| 127,500 | 17 | -20 | In-band | -20 | Pass |
| 128,750 | 1.7 | 0 | In-band | 2.5 | Pass |
| 133,750 | 1.7 | 0 | In-band | 2 | Pass |
| 135,000 | 17 | -20 | In-band | -35 | Pass |
| 141,250 | 17 | -20 | In-band | -48 | Pass |
| 142,500 | 1.7 | 0 | In-band | 11 | Pass |
| 146,250 | 1.7 | 0 | In-band | 0 | Pass |
| 147,500 | 17 | -20 | In-band | -20 | Pass |
| 155,000 | 17 | -20 | In-band | -35 | Pass |
| 200,000 | 54 | -30 | Out-band | -85 | Pass |
| 300,000 | 170 | -40 | Out-band | -116 | Pass |
| 500,000 | 170 | -40 | Out-band | -148 | Pass |

TABLE IV. FILTER DESIGN SPECIFICATIONS AND CALCULATIONS

| Specifi-cation | OUT-BAND | | | | | | IN-BAND MARK | | | | | | IN-BAND SPACE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stage 1 | | Stage 2 | | Stage 3 | | Stage 1 | | Stage 2 | | Stage 3 | | Stage 1 | | Stage 2 | | Stage 3 | |
| **BW** | 30.0 | kHz | 18.0 | kHz | 17.0 | kHz | 17.0 | kHz | 17.0 | kHz | 12.0 | kHz | 17.0 | kHz | 17.0 | kHz | 12.0 | kHz |
| **Center F** | 121.5 | kHz | 152.0 | kHz | 136.5 | kHz | 127.5 | kHz | 129.5 | kHz | 125.0 | kHz | 137.0 | kHz | 140.5 | kHz | 136.0 | kHz |
| **Fl** | 114.0 | kHz | 143.0 | kHz | 128.0 | kHz | 119.0 | kHz | 121.0 | kHz | 117.0 | kHz | 129.0 | kHz | 131.0 | kHz | 127.0 | kHz |
| **Fh** | 129.0 | kHz | 161.0 | kHz | 145.0 | kHz | 16.0 | kHz | 138.0 | kHz | 133.0 | kHz | 145.0 | kHz | 150.0 | kHz | 145.0 | kHz |
| **Fr** | 121.3 | kHz | 151.7 | kHz | 136,235 | kHz | 127.2 | kHz | 129.2 | kHz | 124.5 | kHz | 136.8 | kHz | 140.2 | kHz | 135.7 | kHz |
| **Q** | 4.04 | | 8.43 | | 8.01 | | 7.50 | | 7.62 | | 10.42 | | 8.06 | | 8.26 | | 11.3 | |
| **C** | 120 | pF | 120 | pF | 130 | pF | 120 | pF | 120 | pF | 120 | pF | 120 | pF | 120 | pF | 120 | pF |
| **R2** | 88,4 | kOhm | 14.7 | kOhm | 144,012 | kOhm | 156.3 | kOhm | 156.3 | kOhm | 221.4 | kOhm | 156.0 | kOhm | 156.4 | kOhm | 221.50 | kOhm |
| **R1** | 1352 | Ohm | 518 | Ohm | 560 | Ohm | 694 | Ohm | 673 | Ohm | 510 | Ohm | 601 | Ohm | 572 | Ohm | 431 | Ohm |
| **Ar** | 32.68 | dB | 142 | dB | 128 | dB | 113 | dB | 116 | dB | 217 | dB | 129 | dB | 136 | dB | 256 | dB |
| **R1a** | 1352 | Ohm | 518 | Ohm | 560 | Ohm | 695 | Ohm | 673 | Ohm | 510 | Ohm | 601 | Ohm | 572 | Ohm | 431 | Ohm |
| **R1b** | 676 | Ohm | 259 | Ohm | 280 | Ohm | 348 | Ohm | 336 | Ohm | 255 | Ohm | 300 | Ohm | 286. | Ohm | 215. | Ohm |
| **Ao** | 15 | dB | 64 | dB | 58 | dB | 50 | dB | 52 | dB | 97 | dB | 58 | dB | 61 | dB | 115 | dB |

## VI. CONCLUSION

This paper presented a design of a rapid shutdown system receiver architecture utilizing PLC communication. In particular, a band-pass filter has been designed and implemented using a multi-stage band-pass filter at center frequency of 137.5kHz, complying the with rapid shutdown specification set by Sunspec. The implemented circuit proved to be effective in attenuating the single interferer tones as shown in table III, and hence, proved compliant with Sunspec standards. In addition, a signal mixing technique utilizing a Gilbert cell was implemented to further enhance the system overall stability, performance, and adding an extra layer of security and protection.

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