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# Performance Evaluation of Smart Energy Meter Under Conducted RF Disturbances

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## Abstract

Smart energy meters are critical components of modern smart grid infrastructure, enabling accurate energy measurement, real-time monitoring, and reliable data communication. Their deployment in electromagnetically harsh environments makes immunity to conducted Radio-Frequency (RF) disturbances a key requirement for maintaining measurement accuracy and communication integrity. This paper presents an experimental evaluation of the conducted immunity performance of smart energy meters in accordance with the IEC 61000-4-6 standard. The study employs a Coupling/Decoupling Network (CDN) to inject RF disturbances in the 150kHz–80MHz frequency range at defined voltage levels. Functional performance criteria, including energy measurement accuracy, display behaviour, and communication stability, are monitored during the tests. Results indicate that the smart meter maintains compliance at standard test levels; certain susceptibility points were observed in the lower frequency band, affecting communication reliability. The findings contribute to improved Electromagnetic Compatibility (EMC) understanding and reliability of smart metering systems in field environments.

**Keywords:** Conducted Immunity, Conducted RF Disturbance, Electromagnetic Compatibility (EMC), IEC 61000-4-6, Smart Energy Meter, Smart Grid

## 1. Introduction

The deployment of smart energy meters has become integral to modern smart grid systems, enabling efficient energy management, automated billing, and two-way communication between consumers and utilities. These meters integrate measurement, processing, and communication functions, often operating in electromagnetically noisy environments due to the presence of switching devices, inverters, power-line communication systems, and other electronic equipment. Ensuring that smart meters perform reliably under such conditions is essential for maintaining accuracy and data integrity across the grid network[1,2].

EMC is a fundamental requirement for all electronic devices connected to the power network[3,4]. In particular, conducted immunity refers to a device's ability to withstand RF disturbances that are coupled onto its power or signal lines. Inadequate immunity can lead to measurement errors, display malfunctions, or communication failures in smart meters, potentially affecting billing accuracy and grid data reliability. Therefore, assessing and improving conducted immunity performance is a key step toward ensuring the functional robustness of smart metering systems[5,6].

International standards such as International Electrotechnical Commission (IEC) 61000-4-6 specify test methods and performance criteria for evaluating equipment immunity to conducted RF disturbances within the 150kHz to 80MHz frequency range. Compliance with these standards helps ensure interoperability and reliability of devices operating in diverse electromagnetic environments. While many studies have focused on radiated emissions and immunity, there is comparatively limited experimental data published on the conducted immunity behaviour of smart meters, especially in relation to their measurement and communication performance.

This paper presents a systematic experimental study on the conducted immunity performance of smart energy

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meters in accordance with IEC 61000-4-6. The work involves controlled RF injection using a CDN and monitoring of critical functional parameters such as energy measurement accuracy, communication stability, and display operation during exposure. The results are analysed to identify frequency regions where susceptibility may occur and to assess the overall immunity performance of the tested meters. The findings aim to contribute to a better understanding of conducted disturbance effects in smart metering systems and support ongoing EMC compliance efforts in the smart grid domain.

## 2. Literature Review

The increasing penetration of smart meters in power distribution networks has raised growing interest in their EMC performance. Smart energy meters combine metering, microcontroller, and communication modules, which make them susceptible to both conducted and radiated electromagnetic disturbances. Reliable operation under such conditions is essential for maintaining metering accuracy, data integrity, and communication reliability within Advanced Metering Infrastructures (AMI).

Numerous studies have examined the EMC behaviour of electronic metering systems. Early work focused primarily on emission compliance according to Comité International Special des Perturbations Radioélectriques (CISPR) 22/32, ensuring that meters do not emit excessive interference to nearby devices. Subsequent research expanded toward immunity performance, addressing the susceptibility of meters to external disturbances defined in the IEC 61000-4 series of standards. Among these, IEC 61000-4-6 specifies test procedures for evaluating immunity to conducted radio-frequency disturbances in the frequency range from 150kHz to 80MHz, using CDN to inject controlled RF voltages onto the Equipment Under Test (EUT).

Previous investigations, such as those by Raval *et al.*[7] and Kumar and Singh[8], have analysed how conducted RF disturbances affect smart meter communication channels, especially in Power Line Carrier (PLC) and wireless communication modes. Their findings indicated that the lower frequency region (below 10MHz) often produces communication interruptions due to coupling between the disturbance and the meter's signal lines. Patel *et al.*[9] examined the influence of conducted interference on metering accuracy, reporting that certain measurement modules showed transient errors when exposed to high-amplitude signals. Other researchers have explored susceptibility mitigation through improved circuit layout, grounding schemes, and input filtering, although detailed test data for commercially deployed meters remain limited.

Despite these efforts, comprehensive experimental evaluations of conducted immunity on smart meters remain sparse, particularly under standardised test conditions covering the full IEC 61000-4-6 frequency range. Most available works address general EMC compliance or focus on emission characteristics, leaving a research gap concerning the quantitative analysis of immunity performance correlated with functional degradation indicators such as accuracy drift or communication failure. Addressing this gap is crucial for ensuring reliable operation of metering infrastructure in electromagnetically harsh environments, especially as smart grid deployments expand. The present study aims to contribute to this domain by conducting systematic immunity tests on smart energy meters as per IEC 61000-4-6, analysing their performance under controlled RF injection, and identifying the frequency regions associated with susceptibility or performance degradation.

## 3. Objective of the Study

The deployment of smart energy meters in modern power distribution networks necessitates high EMC to ensure reliable measurement and communication performance. While prior studies have evaluated emission and general immunity aspects, limited experimental data exist on the conducted immunity behaviour of smart meters under standardised test conditions. Addressing this gap is essential to assess how conducted RF disturbances influence meter functionality and compliance with international standards.

The primary aim of this work is to experimentally investigate the conducted RF immunity performance of a smart energy meter in the frequency range of 150kHz–80MHz, as defined in IEC 61000-4-6[10-13]. Specific objectives include evaluating operational stability, measurement accuracy, and communication reliability during disturbance exposure. The key objectives and corresponding evaluation parameters are summarised in Table 1.

**Table 1.** Summary of study objectives and evaluation parameters

| Sl. No. | Objective Description | Evaluation Parameter | Standard/ Reference |
|---|---|---|---|
| 1 | Assess the conducted RF immunity of the smart energy meter within 150 kHz–80 MHz | Meter operational stability, display function | IEC 61000-4-6 |
| 2 | Evaluate measurement accuracy under RF disturbance conditions | Active energy error (% deviation) | IS 16444 / Class 1 limit |
| 3 | Examine communication reliability during exposure | Communication frame success rate (%) | DLMS/ COSEM protocol |
| 4 | Identify frequency bands exhibiting susceptibility | Frequency response behaviour | Observation-based |
| 5 | Determine compliance with EMC performance criteria | Functional performance (Criteria A/B/ C/D) | IEC 61000-4-6 |

By achieving these objectives, the study provides valuable insights into the electromagnetic robustness of smart metering systems and supports the development of EMC-compliant designs for future smart grid deployments. The following section presents the experimental setup, instrumentation, and procedures adopted to achieve these goals.

# 4. Test Setup and Methodology

The conducted immunity evaluation of smart energy meters was performed in accordance with the IEC 61000-4-6 standard, which specifies test methods for assessing the immunity of electrical and electronic equipment to conducted RF disturbances (Figure 1). The procedure involves coupling RF signals onto the power and communication lines of the EUT using CDNs while monitoring the functional performance of the device.

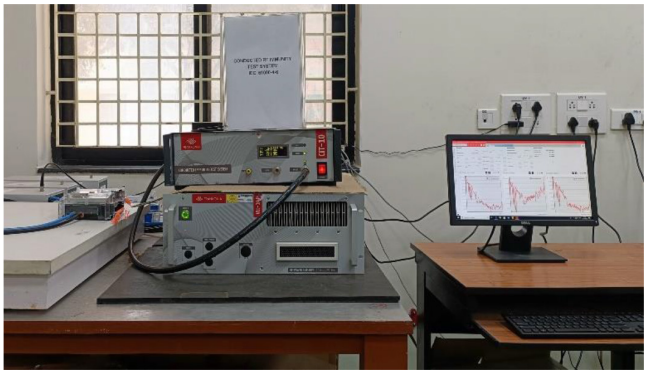


**Figure 1.** Test setup for conducting immunity testing of the smart meter.

## 4.1 Equipment Under Test (EUT)

The equipment under test consisted of a single-phase smart energy meter rated at 240V, 50Hz, with integrated measurement and communication modules. The meter supports both wired and wireless communication interfaces and includes a Liquid-Crystal Display (LCD) for measurement indication. During the test, the meter was powered from a stabilised Alternating Current (AC) source and operated under normal load conditions using a calibrated resistive load to ensure stable measurement readings.

## 4.2 Test Equipment and Configuration

The test system included the following key components:

- RF Signal Generator – Used to produce continuous wave signals within the frequency range of 150kHz to 80MHz.
- RF Power Amplifier – Amplified the generated signal to the required test level.
- Coupling/Decoupling Network (CDN) – Type M2 CDN used for single-phase AC lines, providing coupling of the RF signal onto the power lines while isolating auxiliary equipment.
- EMI Receiver or Spectrum Analyser – Verified the injection level and monitored the disturbance signal.
- Voltage Probe and Calibration Network – Used for pre-calibration and measurement of injected RF voltage levels.

The test setup followed the schematic configuration described in the IEC 61000-4-6 standard. The CDN was connected between the AC supply and the EUT, and the RF signal was injected through the CDN input port. The test environment was configured on a grounded metallic

reference plane, with all cables arranged according to standard recommendations to maintain reproducibility.

### 4.3 Test Signal and Frequency Sweep

The conducted immunity test was performed across a frequency range of 150kHz to 80MHz using a 1% logarithmic frequency step. A dwell time of 3 seconds was maintained at each frequency point to allow the EUT response to stabilise. The test level was set at 3V rms (emf) as specified for residential and light-industrial environments. The modulation applied was a 1kHz sine-wave amplitude modulation with 80% depth, simulating realistic disturbance conditions.

Before testing, the injection level was calibrated using a 150-Ω calibration network to ensure the correct voltage was delivered to the EUT terminals through the CDN.

### 4.4 Performance Criteria and Monitoring

During testing, the following performance parameters were continuously monitored:

- Measurement accuracy: deviation of voltage, current, and energy readings compared with baseline values.
- Display performance: checking for flickering, reset, or display freezing.
- Communication stability: monitoring of data transmission and reception on communication interfaces.

Performance degradation was assessed using IEC 61000-4-6 performance criteria, where:

- Criterion A: Normal performance within specified limits,
- Criterion B: Temporary degradation or loss of function that recovers automatically, and
- Criterion C: Loss of function that requires operator intervention or causes permanent damage.
- Criterion D: Loss of function that cannot be recovered, resulting in permanent degradation or failure of the equipment.

### 4.5 Test Procedure

During testing, the following performance parameters were continuously monitored:

1. The EUT was installed and powered in its normal operational state.
2. RF signals were injected via the CDN while the meter's performance was continuously observed.
3. The test was conducted for both phase-neutral and communication line coupling paths where applicable.
4. Results were recorded at each frequency step, including the observed behaviour and recovery status.

All measurements were conducted in a controlled EMC test laboratory to minimise background interference. The entire test setup was validated before data acquisition to ensure compliance with IEC 61000-4-6 calibration requirements.

## 5. Results and Analysis

Conducted immunity tests were performed on the smart energy meter in accordance with IEC 61000-4-6 over the frequency range of 150kHz to 80MHz at a test level of 3V rms. During testing, the meter was energised at its rated voltage of 240V, 50Hz and loaded with a calibrated resistive load of 10A. Functional performance, measurement accuracy, and communication behaviour were continuously monitored throughout the frequency sweep.

### 5.1 Baseline Performance

Before the application of RF disturbances, baseline measurements were recorded to establish reference operating conditions. The active energy error under normal conditions was measured as –0.12%, while voltage and current readings remained within permissible tolerances. Communication with the head-end system was stable, with no packet loss observed during a 30-minute monitoring period.

### 5.2 Functional Behaviour During RF Injection

The meter maintained continuous operation across the majority of the test frequency range. No resets, display blanking, loss of power, or permanent malfunction were observed. At a limited number of frequencies, temporary disturbances in communication and metrological performance were recorded during RF injection; however, the meter recovered automatically without manual intervention once the disturbance was removed or the frequency was changed.

### 5.3 Frequency-Wise Performance Evaluation

Representative observations at selected frequencies are summarised in Table 2. Temporary degradation was mainly observed in the lower frequency band between 1.8MHz and 2.2MHz, as well as around 10–11MHz, which are known to be susceptible regions due to coupling effects.

**Table 2.** Observed functional performance at selected frequencies

| Frequency (MHz) | Injected Level (V rms) | Error (%) | Communication Status |
|---|---|---|---|
| 0.15 | 3.0 | −0.11 | Normal |
| 0.50 | 3.0 | −0.18 | Normal |
| 1.10 | 3.0 | −0.96 | Normal |
| 1.80 | 3.0 | −1.24 | Temporary delay |
| 2.20 | 3.0 | −1.37 | Packet Loss |
| 5.00 | 3.0 | −0.15 | Normal |
| 10.80 | 3.0 | +1.18 | Short communication delay |
| 20.00 | 3.0 | −0.22 | Normal |
| 80.00 | 3.0 | −0.09 | Normal |

## 5.4 Measurement Accuracy Under Conducted RF Disturbance

Active energy accuracy was continuously logged throughout the immunity test. For most frequencies, the measured error remained within the ±1.0% accuracy limit of a Class 1 meter. However, at a few discrete frequencies, the energy error temporarily exceeded this limit during RF exposure.

The maximum deviation recorded was −1.37% at 2.2MHz. As summarised in Table 3, these deviations were observed only during RF injection and did not persist after the disturbance was removed.

As illustrated in Figure 2, the meter exhibits increased susceptibility at specific frequencies, resulting in temporary energy measurement errors exceeding ±1%, while maintaining stable performance at other frequencies.

**Table 3.** Energy measurement deviation and recovery characteristics

| Frequency (MHz) | Energy Error (%) | Recovery Time (ms) | Post-Test Error (%) |
|---|---|---|---|
| 1.80 | −1.24 | 320 | −0.14 |
| 2.20 | −1.37 | 410 | −0.13 |
| 10.80 | +1.18 | 290 | −0.12 |

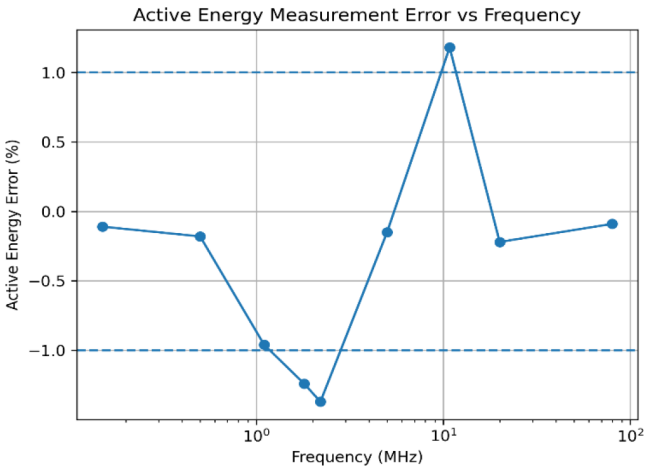



**Figure 2.** Active energy measurement error as a function of injected RF frequency during conducted immunity testing.

## 5.5 Communication Performance Analysis

The communication performance of the smart energy meter was evaluated by monitoring Device Language Message Specification/ Companion Specification for Energy Metering (DLMS/COSEM)- based data exchange between the meter and the data acquisition system (Figure 3) during conducted immunity testing. Packet Success Rate (PSR) was measured over a 60-second dwell time at selected test frequencies by analysing the successful reception of DLMS/COSEM Application Protocol Data Units (APDUs), including GET, SET, and Association Request/ Association Response (AARQ/ AARE) association frames[14].

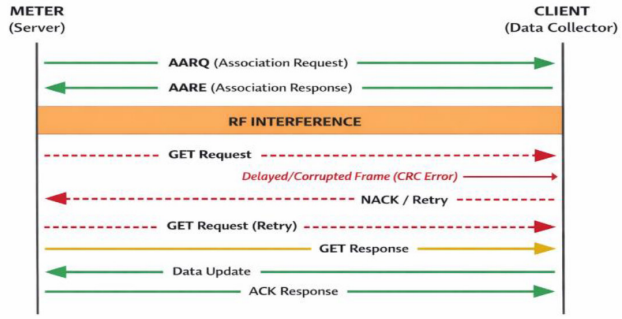



**Figure 3.** DLMS/COSEM communication sequence during conducted immunity testing.

During RF injection, the meter continued to respond to DLMS/COSEM requests across the majority of the frequency range without loss of association or session termination. However, at a few susceptible frequencies, a slight reduction in PSR was observed, corresponding to temporary disturbances in frame transmission. These disturbances manifested primarily as delayed acknowledgements, frame retries, and occasional checksum validation failures at the data link layer, as summarised in Table 4.

**Table 4.** Communication performance during the conducted immunity testing

| Frequency (MHz) | Packet Success Rate (%) | Recovery Time (ms) |
|---|---|---|
| 0.50 | 100 | 0 |
| 1.80 | 96.8 | 180 |
| 2.20 | 95.5 | 220 |
| 10.80 | 97.2 | 160 |
| 20.00 | 100 | 0 |

At 1.8MHz and 2.2MHz, the observed reduction in PSR was primarily due to temporary retransmission of DLMS/COSEM frames, triggered by timeouts in the client–server communication sequence. Despite these transient effects, the DLMS/COSEM association remained intact, and no session resets or authentication failures were observed.

At 10.8MHz, short communication delays were recorded, resulting in marginally increased response times for GET requests. These delays were resolved automatically once the RF disturbance ceased, with communication stability restored within 220 ms, as indicated by the measured recovery time.

During conducted immunity exposure at select frequencies, temporary degradation in communication performance was observed, including reduced packet success rate and brief interruptions in frame exchange during RF injection. Normal DLMS/COSEM communication was automatically restored after disturbance removal without meter reset or data loss, satisfying IEC 61000-4-6 Performance Criterion C.

Figure 4 shows a marginal reduction in packet success rate at susceptible frequencies, attributed to transient frame errors and retries in DLMS/COSEM communication.

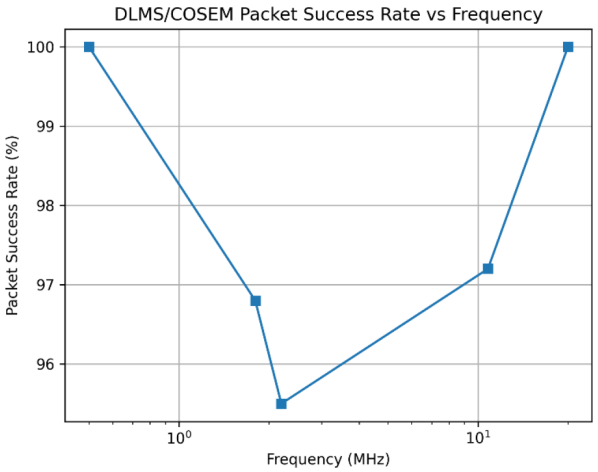



**Figure 4.** Variation of DLMS/COSEM packet success rate with injected RF frequency.

## 5.6 Post-test Verification and Compliance Assessment

Following completion of the conducted immunity test, a post-test accuracy verification was carried out under normal operating conditions. The active energy error returned to 0.13%, closely matching the pre-test baseline value. No residual offset, permanent drift, or data corruption was detected.

Temporary metrological deviations and brief communication disturbances were observed at select frequencies during RF injection; however, all effects were self-recovering after disturbance removal, with energy measurement satisfying Performance Criterion B and DLMS/COSEM communication satisfying Performance Criterion C under IEC 61000-4-6. The meter exhibited baseline electromagnetic robustness, with metrological and communication performance meeting the applicable IEC 61000-4-6 performance criteria, as summarised in Table 5.

**Table 5.** Performance criteria compliance summary

| Function | Observed Behaviour | Performance Criterion |
|---|---|---|
| Energy Measurement | Temporary deviation beyond accuracy class at select frequencies | B |
| DLMS/COSEM Communication | Temporary loss/ degradation during RF injection, auto-recovery post-test | C |
| Meter Operation | Continuous operation without reset | A |
| Data Integrity | No corruption or loss | A |

## 6. Recommendation for Inclusion in Indian Standards

At present, conducting RF immunity testing as specified in IEC 61000-4-6 is not explicitly addressed in existing Indian Standards applicable to static and smart energy meters, such as Indian Standards (IS) 16444, IS 13779, and IS 14697, which primarily focus on functional performance, safety, accuracy, and selected electromagnetic compatibility requirements. While these standards provide a comprehensive framework for meter performance and reliability, the RF immunity aspects remain outside their current scope.

The experimental results presented in this study demonstrate that conducted RF disturbances can lead to frequency-dependent deviations in energy measurement accuracy and transient degradation in communication performance, even though the meter continues to operate without permanent malfunction. In particular, temporary deviations exceeding the specified accuracy class and momentary reductions in DLMS/COSEM packet success rate were observed at certain frequencies during RF injection.

With the increasing deployment of smart meters in electrically noisy environments—characterised by switching power supplies, communication equipment, and power electronic loads—the likelihood of conducted electromagnetic disturbances coupling onto meter terminals is expected to increase. In such scenarios, the absence of a conducted RF immunity evaluation during type testing may allow certain susceptibility mechanisms to remain undetected until field deployment.

Based on the observations of this study, it is recommended that RF immunity testing, harmonised with IEC 61000-4-6, be considered for inclusion in future revisions of Indian Standards such as IS 16444, IS 13779 and IS 14697[15]. Incorporating this test would strengthen the EMC assessment framework for smart energy meters and enhance confidence in their long-term performance and reliability within evolving smart grid infrastructures.

## 7. Conclusion

This paper presented an experimental investigation of the RF immunity performance of a smart energy meter, evaluated in accordance with IEC 61000-4-6 over the frequency range of 150kHz to 80MHz at a test level of 3Vrms. The meter was operated under rated electrical and communication conditions to assess its susceptibility to conducted RF disturbances representative of practical smart grid environments.

The experimental results indicate that, while the meter remained operational throughout the test, both metrological and communication performance exhibited frequency-dependent sensitivity under RF injection. At several discrete frequencies, the active energy measurement error temporarily exceeded the Class 1 accuracy limit, and transient degradation in DLMS/COSEM communication, including brief frame interruptions and increased response latency, was observed. These effects, classified under Performance Criteria B and C, respectively, suggest coupling of conducted RF disturbances into internal measurement circuitry and communication interfaces. Although the disturbances were reversible after removal of the RF injection, their occurrence highlights limited immunity margins in the present meter design.

Overall, the findings demonstrate that conducted RF disturbances can induce measurable degradation in both measurement accuracy and communication performance, even in the absence of permanent malfunction. This underscores the need for enhanced conducted immunity at the meter design level, particularly through improved grounding, filtering, and shielding techniques. The study further emphasises the importance of incorporating conducted RF immunity evaluation into meter qualification and standardisation processes to ensure reliable and resilient operation of smart energy meters in electromagnetically complex utility environments.

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## Author Contribution:

Hari Prasad Musham: Conceptualization, experimental design, conducted immunity testing, data acquisition & analysis, writing – original draft preparation. D. Shankar: Conducted immunity testing, Data analysis, interpretation of results, literature review support. Jayadev B.L. & Shankara Murthy: Experimental setup support, instrumentation, validation of test procedures. S. Sudha: Review and editing, critical revision, final manuscript validation.