ABSTRACT  Electromagnetic interference (EMI) compliance is a requirement for most electronic systems and devices, including power electronics. The emergence of power electronic systems designed with wide band-gap (WBG) semiconductors poses new challenges for compliance. This is due to the high edge rates achievable with WBG devices, coupled with unintentional grounding paths, some of which are introduced galvanically with traditional EMI compliance instrumentation. This makes it beneficial to use isolated measurement methods in place of traditional ground-referenced EMI instruments. This approach is viable in comparison to traditional EMI compliance measurements and can significantly reduce circulating ground currents, which can greatly impact emissions measurement accuracy. This paper proposes a streamlined method for emissions evaluation of power electronics employing an oscilloscope, differential voltage probes, and post-processing software implemented in MATLAB. This proposed method eliminates unintended metrology ground coupling, yields faster full quasi-peak scan times, and minimizes risk of instrumentation damage.

INDEX TERMS Quasi-peak, QP, common-mode current, electromagnetic interference, EMI, ground current, leakage current, Wide band-gap (WBG) converters, root-sum-of-square (RSS).

I. INTRODUCTION
Electromagnetic interference (EMI) compliance testing is a time-consuming and expensive process, which requires specialized equipment such as EMI receivers and line impedance stabilization networks (LISNs). Conventional test methods may introduce new challenges when evaluating WBG-based power electronic converter systems such as that presented in [1], [2]. As shown in Fig. 1, connecting a ground-referenced EMI receiver to this type of converter system creates additional galvanic common-mode (CM) paths from the source filter (C_Y) [3] and power module parasitic capacitances (C_{ug}, C_{ag}, and C_{lg}) [4] through the EMI receiver’s earth ground connection. These paths, displayed in Fig. 1 as solid black lines for galvanic and brown dotted lines for parasitic, involve implicit capacitive couplings in the power source (C_Y), the simulated motor load (R_{load} and C_{sg}), the neutral connection point (C_{ng}), and the power module(s) (C_{ug}, C_{ag}, and C_{lg}) employed in the converter itself. The CM loop introduced by the galvanic instrumentation ground can dramatically impact the EMI behavior and compliance performance of this system, as reported in [1], [2]. One approach to address this problem is to utilize an alternate measurement method such as an oscilloscope with isolated voltage probes to obtain LISN measurements for compliance. However, adopting this approach introduces two potential challenges. The first challenge is ensuring that the alternate instrumentation has comparable accuracy to the traditional instrumentation. The second challenge is implementing the particular frequency-domain metrics used for EMI compliance assessment. Compliance is typically evaluated in the frequency domain using metrics such as peak, quasi-peak (QP), and average operators that are applied to the measured spectra. These metrics are not
available in a conventional oscilloscope, which operates in the time domain. Therefore, software methods must be employed to post process the measured time-domain data to complete this compliance analysis. If these challenges can be overcome, the measurement approach described herein will have comparable accuracy of compliance assessments for WBG-based power electronic systems.

EMI compliance is evaluated against quasi-peak (QP) and average limits per 47 CFR part 15 [7]. A significant challenge associated with these compliance measurements is achieving full-band QP and average data given the time constants and dwell time requirements of [7], which are adopted from and defined in the CISPR 16-1-1 standard [6]. Many researchers have identified QP as the critical quantity for evaluating EMI compliance [8], [10], [11]; while [12] stresses that the QP measurement is of greatest importance. This work affirms that QP data is of greatest significance since it is responsible for most conducted EMI compliance failures. In the authors’ experience, a device under test (DUT) will often comply with average limits but violate QP limits or pass QP limits with insufficient margin.

A typical EMI receiver requires that the user select points of interest from the peak output and then QP and average values are produced only for these selected frequency ranges. Muller makes this recommendation as one of the QP time saving principles outlined in [13]. This method is recommended because computing full-band QP data over the entire compliance band often requires several hours or more [9]. However, this timesaving approach, which relies on the operator selecting ranges of interest, could lead to false compliance passes because exceedances may exist in omitted sections of the scan. On the other hand, a designer may incur unnecessary cost to improve a peak exceedance that may be compliant when properly measured and evaluated as QP.

Considering these recognized challenges, significant efforts have been undertaken to provide full-band QP and average spectra with fast execution time. For example, some instrument vendors have developed hardware that is specifically designed to perform fast QP computations. One such instrument, the Gauss Instruments TDEMI X [14], is marketed as being 64,000 times faster than conventional EMI receivers. However, instruments with high-speed analysis capabilities are prohibitively expensive. Another approach is the development of “offline” computational tools that can compute QP spectra from recorded experimental data or simulation predictions. For example, L. Yang and S. Wang [15] and Karaca et al. [10] offer predictive EMI performance analysis tools with fast computation times. These methods work in the frequency domain and rely on approximations for calculations of the compliance variables. Krug and Prusser [16] offer a similar frequency-based method. Their approach dramatically reduces peak scan times and offers some improvements for the computation of QP spectra as well. Giezendanner et al. [22] introduce a method of computing QP spectra in the time-domain and discuss the computational challenges associated with this approach.

This paper presents an alternative approach for achieving full-band QP and average spectra. The proposed algorithm is implemented in MATLAB and is referred to as the MATLAB EMI receiver emulator (MERE). MERE works exclusively in the time domain, which stands in contrast to the frequency-domain methods utilized by most of the existing state-of-the-art implementations [10], [15], [16], [17]. This eliminates the need for approximations to deliver the compliance metrics, which provides improved accuracy. Through the application of initial conditions during each computation step, MERE delivers the full complement of compliance spectra (peak, QP, and average) approximately 75% faster than a typical instrument excluding lab and instrument setup time.

The contributions of this work are as follows. First, this paper proposes an isolated method for measuring the conducted emissions of power electronic systems. This method minimizes circulating currents through the instrumentation. Second, it demonstrates that the alternate measurement setup necessary to implement this approach can exceed the accuracy of conventional EMI receivers when attenuation is required. Third, it offers a data post processing tool (MERE) that can efficiently produce full-band emissions metrics that are comparable to those produced by commercial EMI receivers. Last, empirical data is presented showing the significant impact EMI receiver ground paths present to compliance measurement accuracy.

The organization of this paper is as follows. Section II analyzes the accuracy of a conventional EMI receiver compared to the proposed alternate measurement setup, referred to as the “isolated” approach. Section III discusses the requirements and operation of EMI receivers. Section IV describes the design and operation of the MATLAB EMI receiver emulator (MERE) post processing tool. Section V compares the performance of MERE to commercial EMI receivers across multiple test cases and analyzes the impact of circulating ground currents in the conventional setup. Section VI concludes the paper.

![FIGURE 1. EMI Converter Testbed of [1], [2] with induction motor load [5] showing CM loops.](image-url)
II. ACCURACY ANALYSIS OF ALTERNATE EMI MEASUREMENT SYSTEM

The first step in verifying the proposed isolated approach involves evaluating the accuracy of the isolated instrumentation setup compared to the conventional EMI receiver setup. Table 1 presents a calculated amplitude accuracy comparison of three candidate measurement setups computed from parameters provided in their respective datasheets: (1) the Gauss Instruments TDEMI X EMI receiver [14], (2) the Keysight N9038 EMI receiver [23], and the proposed isolated setup. Frequency accuracy of an oscilloscope is difficult to determine for this type of application. Therefore, this comparison focuses on the amplitude accuracy of the instruments as this comparison is possible to perform analytically. It is noted that an empirical validation of the isolated metrology accuracy (which reflects both the amplitude and frequency components) is included in Section V. The isolated measurement setup consists of a Tektronix 5-series MSO oscilloscope [25] and a Tektronix THDP0200 isolated voltage probe [26]. For the conventional EMI receiver, measurement accuracy and optional attenuator accuracy values are considered in the summary. For the isolated setup, oscilloscope resolution, oscilloscope gain, probe gain, and probe bandwidth accuracies are included in the accuracy summary. The root-sum-of-squares (RSS) technique [24] was employed to combine the accuracy components of each system to yield overall system accuracy. For the conventional setup, the overall accuracy is computed as follows:

$$a_{con} = \sqrt{(a_M)^2 + (a_A)^2} \tag{1}$$

where $a_M$ and $a_A$ are the EMI receiver measurement and attenuator accuracies, respectively. For the isolated setup, the overall accuracy is computed as follows:

$$a_{alt} = \sqrt{(a_R)^2 + (a_G)^2 + (a_{PG})^2 + (a_{PB})^2} \tag{2}$$

where $a_R$, $a_G$, $a_{PG}$, and $a_{PB}$ are the oscilloscope resolution, gain, probe gain, and probe bandwidth accuracies, respectively.

For the conventional setup, typical or 95th percentile accuracies were used in place of worst-case values. For the isolated setup, accuracy is presented for three resolution settings of the oscilloscope in terms of effective number of bits (ENOB). The first setting corresponds the ENOB value for an inexpensive oscilloscope, while the other two settings correspond to the ENOB values for high-end instruments. Surprisingly, oscilloscope resolution is not a major contributor to the overall system accuracy, which is dominated by the contribution of the 1.5 kV isolated differential voltage probe used in this setup. It is noted that the relative importance of the individual contributions will be influenced by probe selection and therefore by the voltage level of the system under test. This analysis demonstrates that the isolated setup is expected to have similar error to the conventional setup, according to instrument specifications. However, the accuracy of the conventional setup will also be influenced by the presence of inline attenuation. The use of external attenuators is usually required to protect the instrument input when measuring power electronic systems with an EMI receiver. Table 1 presents an additional configuration for each EMI receiver that reflects the influence of adding a HAT-20+ coaxial 20 dB attenuator [27] to the signal chain. These configurations demonstrate that an additional accuracy degradation of approximately 2% is incurred by the use of external attenuation. This can be a significant consideration depending on the amount of attenuation required given that CISPR 16-1-1 [6] specifies an accuracy of better than +/- 2 dB in the band B frequency range.

III. EMI RECEIVER REQUIREMENTS AND OPERATION

This section describes the operation of a typical EMI receiver.

A. APPLICABLE STANDARD AND FREQUENCY BAND

The scope of this paper focuses on the conducted emissions requirements for class A and B unintentional radiators per 47 CFR part 15 [7], which are subject to conducted compliance in band B (150 kHz–30 MHz). This category covers a vast population of devices that face significant EMI challenges, many of which are caused by power switching circuits.

B. MEASUREMENT SYSTEM AND COMPLIANCE LIMITS

Compliance to 47 CFR part 15 conducted emissions requirements is determined by measurements acquired from an EMI receiver connected at the measurement ports of 50 μH/50 Ω line impedance stabilization networks (LISNs) [7]. The LISNs are connected in the power path of the DUT allowing conducted emissions to be evaluated per the requirements set forth in [7]. Specifically, the measurements are performed in the frequency range defined by CISPR 16-1-1 [6] and compared to the limits described in Table 2. It is noted that the compliance limits are imposed as QP and average quantities rather than peak quantities. The QP measurement is not straightforward as it is intended to “weigh” the repetitiveness of reoccurring peaks. This weighing operation can be modeled by the capacitor voltage in the analog circuit shown in Fig. 2. In this circuit, the capacitor voltage is subject to two different time constants, as shown in Table 2. The charge time, or “attack time” is determined by $R_C \cdot C$; while the discharge time, or “decay time” is determined by $R_D \cdot C$. Since the attack time
TABLE 2. Conducted Limits and Quasi-Peak Time Constants [7]

| Emission Frequency (MHz) | Conducted Limits (dBmV) |          |          |
|------------------------|-------------------------|----------|----------|
|                        | Class A                | Class B  |
|                        | QP   Ave | QP   Ave |          |
| 0.15 - 0.5             | 79    66   | 66 to 56 | 56 to 46 |
| 0.5 - 5                | 73    60   | 56      | 46       |
| 5 - 30                 | 73    60   | 60      | 50       |

FIGURE 2. Quasi-peak detection circuit [20].

FIGURE 3. Example block diagram of EMI receiver consisting of swept spectrum analyzer with added preselector, preamplifier, and quasi-peak/average detector [6].

is much shorter than the decay time, the capacitor voltage is correlated to the frequency of pulse repetition. It should be noted that modern EMI receivers implement this weighting function in software rather than with analog circuitry.

C. EMI RECEIVER OPERATION

The EMI receiver general operation shown in Fig. 3 can be described by the following sequence. First, the RF signal measured at the LISN is preconditioned via an attenuator, preselection filter, and preamplifier. The signal is then mixed with the sweep generator, which is the prescribed method of stepping through the selected band. At each step, the signal is processed by the intermediate filter (IF) at the specified resolution bandwidth (RBW), which is 9 kHz for band B. Next, the signal is demodulated with an envelope detector. Finally, the QP and average values are computed, and the process is repeated at each frequency step until the end of the measurement band is reached. EMI receivers may allow for configurable step size, which should be less than the IF 6 dB RBW (Table 2). Typically, the step size is set to 1/2 the RBW value [9], [18]. In general, the compliance measurement block that computes the quasi-peak and average spectra is the most computationally intensive step of the system [12], [13].

It is noted that the standard includes tolerance and variation criteria for certain portions of the procedure shown in Fig. 3, such as the shape of the IF filter roll-off [6]. To understand the impact of these parameters on compliance measurements and establish an acceptable variance threshold, three CISPR 16-1-1 compliant, commercial EMI receivers were compared experimentally: the Gauss Instruments TDEMI X, the Rohde & Schwarz FSH20, and the Keysight N9038A. Each instrument was configured with identical parameters and connected to an arbitrary waveform generator configured to produce a 400 kHz square wave. This signal was chosen as a reference due to its rich harmonic content, which provides a multitude of peak comparison points. An overlay of the peak, QP, and average spectra produced by these instruments are included in Fig. 5. The results demonstrate observable differences, particularly with wide separation in the noise floors. On the other hand, the fundamental and harmonic peaks agree within approximately 2.5 dB across the entire measurement band. Discussions with instrument manufacturers revealed a significant level of proprietary content in the implementation of the standard procedure shown in Fig. 3, which may account for the observed differences. It is noted that this comparison was performed multiple times, with similar results observed in every case. This demonstrates that CISPR 16-1-1 compliant instruments may differ in the peak, QP, and average spectra computed for a given signal by as much as 2.5 dB. It is further noted that MIL-STD-461G [19] specifies a 3 dB variance acceptance criterion for LISN attenuation over frequency. This specification is not related to the accuracy of the measurement receiver used in MIL-STD-461G. However, this specification nevertheless reinforces that 2.5 dB may be an acceptable variance for compliance measurements performed with different instruments.

IV. MATLAB EMI RECEIVER EMULATOR (MERE)

The MATLAB EMI receiver emulator (MERE) is a custom software package written in MATLAB that calculates EMI performance metrics comparable to those produced by a CISPR 16-1-1 compliant EMI receiver. This tool or a similar method is necessary to utilize the isolated measurement setup proposed in this paper for EMI compliance evaluation. MERE performs all operations in the time domain, after reading input from a data file. The content of this file may represent waveforms produced by a circuit simulator or measured signals from an oscilloscope or data logger. In either case, the data should represent LISN voltages that are measured in the same manner described previously. The input file contains the instantaneous time and LISN voltage magnitude for a recommended minimum duration of 70 switching cycles to ensure capture of system anomalies. The sample rate for the LISN voltage measurements should be at least eight times greater than the highest frequency of interest (30 MHz for band B).
FIGURE 4. MERE Functional Block Diagram for CISPR band B.

FIGURE 5. (a) Peak EMI performance comparison plots for a 400 kHz square wave stimulus. (b) QP EMI performance comparison plots for a 400 kHz square wave stimulus. (c) Average EMI performance comparison plots for a 400 kHz square wave stimulus.
The operation of the MERE process is shown in functional block form in Fig. 4. To start the process, data is imported into the MATLAB environment as a numerical table. The frequency sweep loop is initialized to the start of the frequency band. This loop sweeps the center frequency \( f_c \) across the measurement band at the prescribed increment of 1/2 the required IF filter RBW, which is specified in Table 2. During each iteration in the calculation loop, the time-domain data is resampled at the sampling frequency \( f_s \) which is critical for optimizing the resulting vector length to achieve a balance between computational efficiency and accuracy. By executing a large number of experiments, it was determined that the best results are obtained in the range \( 4f_s \leq f_s \leq 8f_c \). After the input data is resampled, it is processed through the IF filter. A Gaussian filter was implemented using the MATLAB signal processing toolbox. Other filter types were trialed and produce comparable peak results. This filtered data is then processed through the MATLAB envelope function.

The peak and average values are determined by applying the MATLAB max and average functions to the output vector of the envelope function. However, quasi-peak is significantly more challenging as it requires numerically solving two differential equations based on the two operating points of the quasi-peak detection circuit of Fig. 2. These two operating points correspond to the two diode conduction modes.

When the diode is conducting \( (i_C > 0) \), the current through the capacitor is:

\[
i_C = \frac{v_{IF} - v_C}{R_C} - \frac{v_C}{R_D} = C \frac{dv_C}{dt}
\]

(3)

where \( v_{IF} \) is the output voltage of the IF filter, \( v_C \) is the capacitor voltage, \( R_C \) is the charge resistor, and \( R_D \) is the discharge resistor. Rearranging (3) and recognizing from Fig. 2 that \( v_{QP} = v_C \) yields

\[
v_{QP} = \int \left( \frac{v_{IF} - v_{QP}}{R_C \cdot C} - \frac{v_{QP}}{R_D \cdot C} \right) dt
\]

(4)

where \( v_{QP} \) is the quasi-peak output voltage. Converting to the Forward Euler form yields the first equation for numerical analysis:

\[
v_{QP}(n+1) \approx h \cdot \left( \frac{v_{IF}(n) - v_{QP}(n)}{R_C \cdot C} - \frac{v_{QP}(n)}{R_D \cdot C} \right) + v_{QP}(n)
\]

(5)

where \( h \) is the integration time step. When the diode is not conducting \( (i_C < 0) \), the current through the capacitor is:

\[
i_C = -\frac{v_C}{R_D} = C \frac{dv_C}{dt}
\]

(6)

where \( R_D \) is the discharge resistor. Rearranging (6) and recognizing from Fig. 2 that \( v_{QP} = v_C \) yields

\[
v_{QP} = \int \left(-\frac{v_{QP}}{R_D \cdot C} \right) dt.
\]

(7)

Converting to the Forward Euler format yields the second equation for numerical analysis:

\[
v_{QP}(n+1) \approx h \cdot \left( -\frac{v_{QP}(n)}{R_D \cdot C} \right) + v_{QP}(n).
\]

(8)

These two states are summarized by

\[
v_{QP}(n+1) \approx \begin{cases} 
  h \left( -\frac{v_{QP}(n)}{R_D \cdot C} \right) + v_{QP}(n) & i_C > 0 \\
  h \left( \frac{v_{IF}(n) - v_{QP}(n)}{R_C \cdot C} - \frac{v_{QP}(n)}{R_D \cdot C} \right) + v_{QP}(n) & i_C < 0.
\end{cases}
\]

(9)

The forward Euler equations (9) were implemented in a nested loop in the calculation block of Fig. 4 to numerically solve for the QP voltage. Finally, \( f_c \) is incremented by 1/2 the RBW value, and the process is repeated until the end of the measurement band is reached. It is noted that all operations are performed in the time domain, including the application of the IF filter. The computational burden can be significantly reduced by the careful application of initial conditions. Initial conditions can be inferred from the known relationship between the four following magnitude metrics [20]:

\[
\text{Peak} \geq \text{QP} \geq \text{RMS} \geq \text{Average}
\]

(10)

Thus, the initial value for the QP numerical integration can be set to the RMS value of the envelope detector, which greatly reduces the number of iterations required to reach the final value at each \( f_c \) frequency step.

Given the operational implementation of the commercial instruments is proprietary, the MERE tuning process is completed through iterative experimental comparisons. The primary sensitivity of the tuning process is the selection of the IF filter type, filter parameters, and sampling frequency \( f_s \). For the Gauss instrument, a Gaussian filter was selected based on the instrument results and the parameters were adjusted to achieve the strongest agreement with the instrument’s noise floor. Note the peak values vary little during this adjustment. The frequency step should also be tweaked to match the instrument settings.

It is noted that the results shown in the data tables of Fig. 5 do not strictly obey (10) due to the selection of the reference signal. It is well known that continuous, unmodulated signals, such as the square-wave reference signal used in this example, produce equal values for all detectors [20]. Thus, any variance observed between the peak, QP, and average values reported in Fig. 5 is likely the result of measurement noise.

V. METHOD VERIFICATION

A. FUNCTION GENERATOR VALIDATION

For verification, the output of MERE was also compared to peak, QP, and average measurements with the three commercial EMI receivers shown in Fig. 5. As observed in this figure, MERE produces good agreement with the EMI receiver measurements for all peaks. MERE predictions average within 2 dB of all EMI receiver measurements over the entire band for peak, QP, and average results. Specifically compared to the Gauss TDENIX instrument, MERE is within 2 dB of
each peak with the exception of 20.4 MHz data point. Several MERE parameters including filter type, filter order, sampling frequency, and signal vector length were specifically tuned to achieve the agreement to the Gauss TDEMI X measurement. This procedure is straightforward, and MERE can be readily tuned to match the performance of other instruments. This tunability highlights one of the ancillary benefits of MERE over single-instrument analysis, as it provides a measure of insight into the sensitivity of parameters that are employed while implementing the analysis procedure shown in Fig. 3. It is also noted that the results in Fig. 5 were produced by MERE in 44 minutes running on a standard 2.7 GHz laptop. By comparison, a conventional EMI receiver required almost four hours to complete analysis of the same reference signal.

B. WBG-BASED CONVERTER VALIDATION

The efficacy of the proposed isolated measurement approach was further evaluated through an experimental study involving a WBG-based single-phase inverter. This inverter utilizes a single commercially available 1.2 kV SiC MOSFET half-bridge power module from Wolfspeed (CAS120M12BM2). For all experiments reported here, the inverter was operated at 177 kHz using complementary PWM with a fixed 50% duty cycle. The load of this converter is designed to simulate the impedance of one phase of a three-phase motor, with a reasonable parasitic coupling to the chassis of the machine, which is assumed to be bonded to earth ground for safety reasons. In this study, the notional schematic shown in Fig. 1 was realized in hardware by making minor adjustments to the EMI testbed previously presented in [2]. The hardware realization of this system is shown in Fig. 6 and Fig. 7. Two experiments were performed using this configuration as described in Table 3 and the operating conditions and metrology components are summarized in Table 4.

In the first experiment, the testbed was operated with a conventional EMI receiver (Keysight N9000A) connected to the DC- LISN measurement port. The EMI receiver was attached using attenuators to achieve 60 dB of total attenuation. This was necessary to reduce the unfiltered LISN voltage from an unattenuated value of 30.9 dBm to a level that would not damage the EMI receiver input. The EMI receiver was powered through a Tripp-Lite IS1000 isolation transformer to minimize CM currents through the instrument’s power leads. A second, standalone 50 Ω terminating resistor was connected to the DC+ LISN measurement port, which was not instrumented. This configuration is representative of the conventional EMI compliance setup. Simultaneously during this experiment, an isolated voltage probe was used to measure the DC- LISN in the time domain. These specific measurements are shown in Fig. 7(a) and (b). The data recorded from this probe was later analyzed using the MERE method. This experiment serves two purposes. First, it provides further opportunity to validate the output of the MERE method against EMI receiver measurements. This analysis is more representative of a power electronic converter compliance setup compared to the validation studies presented in the previous section. Second, this study provides a mechanism to directly evaluate the impact of the spectrum analyzer on the resulting emissions measurements.

In the second experiment, the spectrum analyzer was removed and the DC- LISN measurement port was connected to a standalone 50 Ω terminating resistor. In this configuration, the isolated voltage probe remained attached to the DC- LISN measurement port to measure the LISN voltage in the time domain. This metrology is demonstrated in Fig. 7(c), and the details of these two experiments are summarized in Table 3. The time-domain LISN voltage measurements from both experiments were analyzed using the MERE method for subsequent comparison and analysis.

The results of Experiment 1 are presented in Fig. 8(a) for the two measurement methods. In this experiment, the MERE method output and the EMI receiver measurements demonstrate strong agreement across the entire CISPR frequency range. Specifically, the MERE method output and the EMI

| #  | Metrology          | Description               |
|----|--------------------|---------------------------|
| 1  | EMI Receiver & Oscilloscope | Simultaneous Time & Frequency Domain |
| 2  | Oscilloscope       | Time Domain Only          |
receiver measurements differ by an average of only 2.6 dBμV at the fundamental and first five harmonics identified in the table of Fig. 8(a). This agreement is on the same order as the agreement observed between different CISPR 16-1-1 compliant EMI receivers, as described in Section III. This outcome further corroborates the validity of the MERE method for accurately characterizing the EMI performance of WBG-based power electronic systems. Fig. 8(b) presents a comparison of the output of the MERE method from Experiment 1 (EMI receiver connected) and Experiment 2 (EMI receiver disconnected). The most notable feature of this plot is a reduction of 15.7 dBμV in emissions at the switching frequency (177 kHz) when the EMI receiver is disconnected from the system. The emissions profile at higher harmonics is also impacted by the removal of the EMI receiver although to a lesser degree than the fundamental frequency. These differences suggest that the flow of current through the EMI receiver ground connection significantly influences the EMI behavior of the system. Fig. 9 presents a time-domain comparison of the leakage current through the output coupling of the converter load both with the EMI receiver connected (Experiment 1) and without the EMI receiver connected (Experiment 2). The exact measurement locations are shown in Fig. 1. This comparison confirms that the testbed output leakage current increases by nearly 150% RMS when the EMI receiver is attached to the system. Fig. 9 also demonstrates that nearly all of the output leakage current returns through the EMI receiver ground connection when it is attached (Experiment 1). Further testing was conducted increasing the dc bus voltage of the converter system from 600 VDC to 1000 VDC in 100-volt increments. The results, shown in Fig. 10, show a direct increase in EMI receiver ground currents. The plot also shows the minimal ground current impact introduced by the oscilloscope and differential probe instrumentation which is connected in both experiments. Thus, the presence of a ground-referenced EMI receiver introduces a galvanic return path that increases the circulation of CM currents in the system. Additional experiments were performed with varying load resistor values, but the plots were omitted for brevity. The same trends were observed in these alternative operating conditions suggesting this phenomenon is not specific to one set of operating conditions. The presence of this return path significantly influences the emissions behavior of the system under analysis. The net result is an exaggerated emissions profile, especially at the switching frequency, which may lead to an overly conservative design for the emissions control features of the system. It is also noted that this influence is caused by the conventional ground-referenced qualification instrumentation and is artificial in the sense that this influence would not be present in a deployed system.
In addition, the proliferation of circulating CM currents in the system during compliance testing also increases the risk of damage to the instrument itself. During this study, the EMI receiver manufacturers were consulted regarding the allowable level of ground current for these instruments. These discussions revealed that the instruments considered herein may incur internal damage with as little as 1.0 $A_{\text{rms}}$ of ground current. In the authors’ experience, ground current levels far in excess of this threshold occur during steady-state operation at DUT power levels of only a few kilowatts. In fact, the operating conditions utilized for the studies described in this paper were significantly modified to avoid exceeding the safe ground current threshold of the attached instrumentation. Even more concerning is the fact that the safe level of ground current may be exceeded without the operator’s knowledge unless specific provisions are made for measuring this parameter. Such measurements require instrumenting the power cable of the EMI receiver, which is not common practice. Overall, these factors reinforce the need for isolated measurements during EMI compliance assessment of power electronic...
converters, which is one of the principal advantages offered by the proposed isolated method with MERE.

VI. CONCLUSION

This paper introduces an isolated approach for conducting EMI compliance analysis of power electronic converters using an oscilloscope, differential probes, and software-based post processing tool. This method provides two primary benefits for the analysis of WBG-based converters compared to the conventional approach, which involves a ground-referenced EMI receiver. First, the method provides galvanic isolation between the equipment under test and the instrumentation. This isolation reduces the circulation of leakage current through implicit CM coupling paths in the system, which would otherwise return through the EMI receiver ground lead. For the system considered here, the elimination of this leakage path is shown to reduce the conducted emissions at the fundamental frequency by 15.7 dBμV. This finding is consistent with emerging literature claiming that circulating CM currents can dramatically influence the emissions behavior of WBG-based converter systems. Second, the proposed method may also provide measurement accuracy benefits compared to the conventional approach when inline attenuators must be used to protect the input circuitry of the EMI receiver. This paper also introduces a post-processing tool called the MATLAB EMI receiver emulator (MERE), which produces compliance metrics with comparable accuracy to those produced by commercially available EMI receivers. The isolated measurement approach proposed in this paper can be readily implemented with common laboratory instrumentation and is amenable to the analysis of high-power, medium-voltage systems with minimal risk to the instrumentation. Overall, the approach proposed herein is expected to yield improved emissions characterization of WBG-based converter systems, especially in the transition to medium-voltage applications.

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