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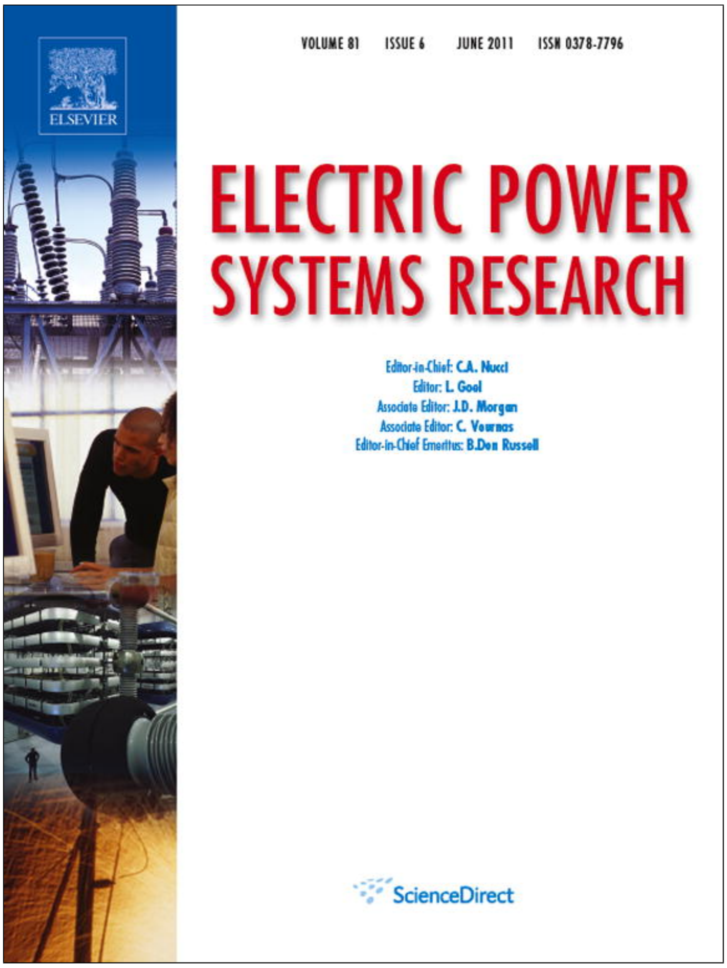

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Electric Power Systems Research 81 (2011) 1215–1226

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Technology assessment for power quality mitigation devices – Micro-DVR case study

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A R T I C L E I N F O

Article history:
Received 25 October 2010
Received in revised form 19 January 2011
Accepted 24 January 2011
Available online 20 February 2011

Keywords:
Power quality
Power electronics
Technology assessment
Power conditioning
Voltage sags
Voltage swells

A B S T R A C T

This work presents a case study on technology assessment for power quality improvement devices. A system compatibility test protocol for power quality mitigation devices was developed in order to evaluate the functionality of three-phase voltage restoration devices. In order to validate this test protocol, the micro-DVR, a reduced power development platform for DVR (dynamic voltage restorer) devices, was tested and the results are discussed based on voltage disturbances standards.

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1. Introduction

Sustained interruptions, which require the repair of distribution circuits, are not the only events that cause problems for electric power customers. The momentary breaker and recloser operations before lockout can be just as detrimental to sensitive end-use equipment as the actual lockout itself. For example, semiconductor-manufacturing plants can be especially vulnerable to momentary interruptions. The total time required to produce a semiconductor chip may be as long as 30 days, with numerous critical processes involved. The chip can be ruined at any time during this process if a voltage sag or momentary interruption causes a sensitive machine to trip or causes an abnormal operation. Other industries that are sensitive to voltage sags and momentary interruptions include plastics, rubber, paper, textiles, glass, automotive, and steel manufacturing plants. Most plants can ride through these voltage drops by virtue of their mechanical and electrical inertia. However, this is not the case with electrically held-in contactors and relays that control the machinery. Contactors can drop out within 5–20 ms after the start of voltage sags as low as 75% of nominal voltage. Often these contactors can be responsible for shutting down the entire installation. These events can be complex, difficult to analyze, and expensive to the electric power customer [1–4].

This paper presents a case study on technology assessment for power quality devices, where a system compatibility[1] test protocol for power quality mitigation devices is developed in order to evaluate the functionality of a three-phase dynamic voltage restoration

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[1] System compatibility can be defined as the ability of an equipment to work as designed in its intended electrical environment (equipment immunity) without adversely affecting the operation of other equipment (equipment emissions).

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doi:10.1016/j.epsr.2011.01.014

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(DVR) device. Section 2 presents a test case power mitigation device, the micro-DVR. Section 3 describes the system compatibility test protocol reasoning, characterization tests applied by using the proposed test protocol and presents experimental results with comments. Section 4 presents the conclusions.

2. Inverter-based sag-mitigation device: the micro-DVR and its family

2.1. Description of the mini-DVR family

Voltage sags[2] and swells are two important factors that adversely impact the productivity of the manufacturing facilities around the world. Because of the growing number of equipment that is being sensitive to the quality of the delivered electrical energy, the use of power quality mitigation device becomes necessary. The DVR (dynamic voltage restorer), a series connected voltage correction device [5–9], is one way to mitigate the power quality disturbances in any industrial facility. Commercial DVR solutions are within the range of MVA, and are typically installed at the factory medium voltage entrance, in order to support the entire plant [10,11].

An alternative DVR solution, called the mini-DVR family [12], is to use DVR equipment at the range of tens of kV A, aiming a power quality solution for one sensitive load in a given plant. This approach could reduce the acquiring costs of a DVR solution. Other economical and technical aspects for this particular solution are addressed below:

- The DVR is always on: one advantage is that the dynamic behavior during voltage disturbances is better than off-line solutions, and one can expect response times of less than half cycle of 60 Hz. The disadvantages are that the DVR power components must be rated at nominal values, related to the load power and the DVR operation losses are not negligible, decreasing the total efficiency of the set *DVR + sensitive load*[3];
- The injection of voltage compensation is made in series between the mains and the load, using three single-phase injection transformers, one per phase, independently controlled. Compensation voltages are synthesized by three one-phase full bridge PWM inverters connected to a common DC link. The three independent series compensators ensure correction of asymmetric voltage disturbances;
- Energy storage is made by the capacitor bank of the DC link. The value of the capacitor bank limits the depth and duration of the correctable voltage disturbance event, and is limited by the maximum physical size of this bank within the equipment. On the other hand, the absence of a battery bank reduces maintenance costs, compared with an UPS solution; and
- As the DVR is always operating, it can be used to filter voltage harmonics of the mains, using its available series injection transformers. The proposed mini-DVR topology (Section 2.2) includes a three-phase PWM rectifier in parallel, which maintains constant voltage at the DC link. This rectifier can also provide current harmonics and reactive power to the mains, acting as an active power filter.

[2] Also known as "voltage dips".

[3] Some DVR strategies keep the power parts of the equipment turned off until the occurrence of voltage disturbances, only turning it on for the duration of such events. The power parts of this kind of DVR can be projected with a fraction of the load rated power, as they operate only during the few cycles of the voltage disturbances, and there are no power parts losses most of the time, increasing overall efficiency. The main issue of this strategy is to guarantee DVR turn on time fast enough to protect the sensitive load.

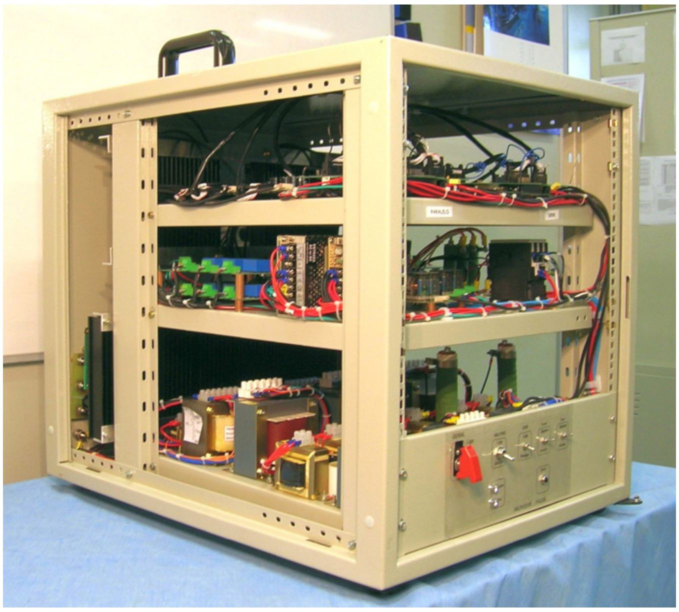

Fig. 1. View of the micro-DVR.

The development of the mini-DVR family imposes the choice of suitable power topologies, and the implementation of control circuits and software. The high voltages and currents (hundreds of volts and amperes) at the equipment impose safety concerns for hardware debugging and increase the risk of equipment damage during software developmental stage. A possible answer for these issues is the micro-DVR [13], shown in Fig. 1. This platform operates with reduced three-phase AC voltage and current levels (31 V RMS phase voltages and 3 A RMS phase currents). Therefore, there is a reduction in system size, allowing an easier handling compared with a real scale system. With reduced current and voltage levels, along with the reduction of hazardous working environment conditions, electromagnetic interference generated by platform's static converters switching is also minimized. Small scale equipment can also reduce development costs. In a small laboratory with limited AC power capability, tests emulating full scale equipment can be done. Human and material resources can also be saved, as less people must be engaged and basic insulation levels both for measurement equipment and IPEs[4] are reduced. With reduced power and size, equipment can be easily transported and operated.

The presence of series and parallel compensation circuits opens the possibility of operating the equipment as a FACDS (flexible alternating current distribution systems) allowing series compensation of distribution lines, as well as power flow control between parallel feeders, as well as an UPFC (unified power flow controller) for distribution systems, turning the micro-DVR into an interesting and valuable tool for personnel training on these new technologies.

Since this small scale equipment is built with all features found in a full scale one, the supervision and control circuit boards, as well as all the associated control hardware, would be the same as those found in a full scale equipment, allowing easier development and debugging of both software and hardware. Power hardware dimensioning and validating strategies can also be studied, considering features that cannot be easily reproduced in a digital simulation environment.

[4] Individual protection equipments.

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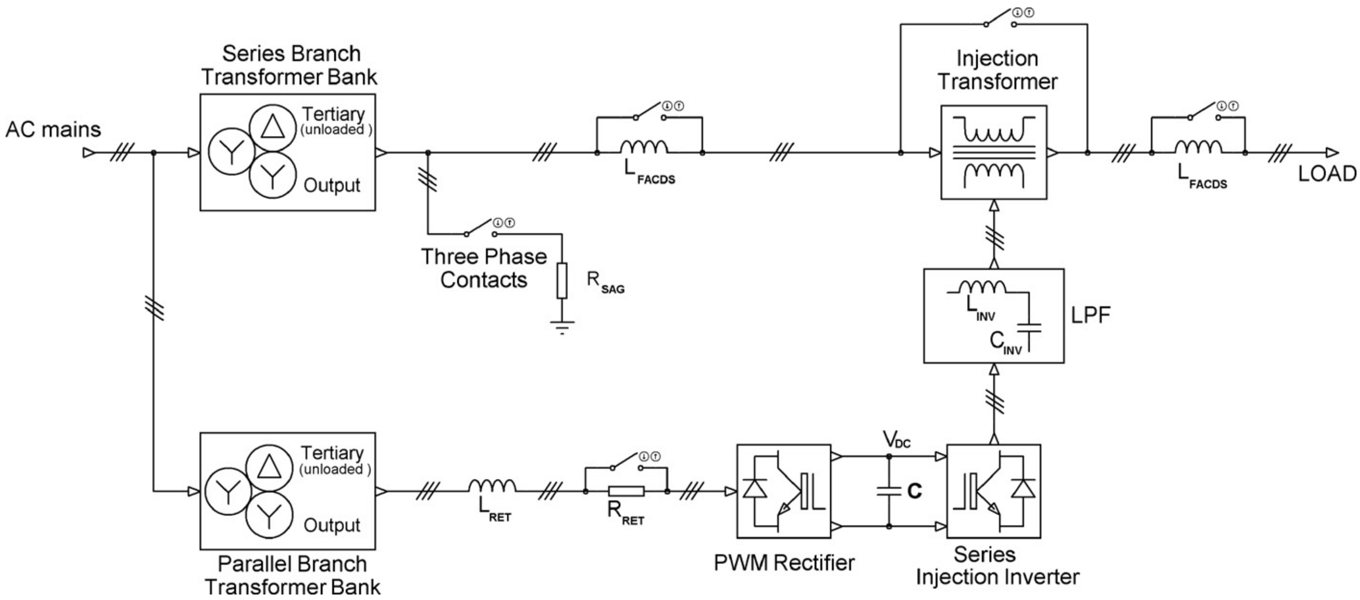

Fig. 2. Simplified single-line diagram of the micro-DVR.

2.2. Operation of micro-DVR

A simplified single-line diagram of the micro-DVR is presented in Fig. 2. The system is connected to the AC mains through two single-phase transformer banks with star–star connection and a delta connected tertiary.[5] This configuration allows operation in phase with the AC mains as well as galvanic insulation. One transformer bank is connected to the series branch, and the other to the parallel branch.

The series branch is implemented with three single-phase full bridge inverters, with three-level switching PWM[6] [14], connected to LC (L_{INV}, C_{INV}) output filters, and series connected between insulated AC side and load through three single-phase injection transformers, allowing zero sequence current injection. The presence of switchable inductors L_{FACDS} allows the emulation of a transmission or distribution line impedance. The R_{Sag} resistor has the same value of the transformer banks series impedance. Its momentary connection generates a three-phase voltage sag to 50% of the nominal phase value. It is introduced in this prototype as a means to simulate balanced three-phase voltage sags and it is not part of the final DVR full scale model.

The parallel branch is composed of the second transformer bank connected to a three-phase PWM rectifier, which absorbs AC sinusoidal currents with high power factor[7] [15] and controls the DC voltage on the bank of capacitors C to $V_{DC} = 50\,\text{V}$ (rated nominal value). In a load rejection event which generates a momentary AC voltage swell, series branch inverters return the energy back to the capacitors bank, and the PWM rectifier, operating as an inverter, returns the energy to the mains. During the initial energization, with the PWM rectifier still turned off, the charging current to the capacitor bank C is limited temporarily by the resistors R_{RET}. When V_{DC} reaches a minimum value, the control system short circuits the resistors R_{RET} and turns on the PWM rectifier, as well as the three series inverters. Due to the boost effect of the PWM rectifier operation, in steady state V_{DC} is higher than the peak line voltage value at the secondary of the parallel branch, allowing the PWM rectifier to impose currents with positive or negative di/dt values on the L_{RET} inductors. The implemented micro-DVR is expected to compensate three-phase voltage sags up to $V_{Sag3\varphi} = 0.5$ pu and voltage swells up to $V_{Swell} = 1.2$ pu with expected maximum duration of $\Delta t = 300$ ms. If sag duration exceeds the maximum time, depleting the energy of the capacitor bank C, reducing DC voltage below a prespecified safety value, the three series inverters resume operation and their respective injection transformers are short-circuited at the load side by mechanical contacts in order to completely bypass the micro-DVR between the source and the load (Fig. 2). Control and reference generation aspects of the micro-DVR are assessed in Refs. [13,16].

3. Experimental results

3.1. Preliminary experimental tests description and results

Some preliminary performance measurements for DVR operation of the micro-DVR were initially made at the University of Sao Paulo, with voltage harmonics compensation (Fig. 3) and three-phase voltage sags to 65%[8] with resistive load (Fig. 4).

These preliminary tests results only indicate that, for some arbitrary voltage disturbances, the equipment performs as expected. To perform a full system characterization of the equipment, one has to impose a methodology based on a existing standard, in order to verify the equipment's compliancy to that standard.

3.2. System compatibility test protocol reasoning and significance of the characterization tests

There are many standards on voltage sag immunity tests [17,18], some still in development [19], and some complementary (or associated) standards [20,21], as well as comprehensive reports on the subject [22]. They make recommendations and obligatory requirements on aspects as sag magnitude and duration, but they are not

[5] Delta connected tertiary avoids output voltage distortion due to the primary side magnetizing current, as the primary and secondary connection is a star–star one.

[6] Also known as unipolar PWM switching [2].

[7] AC current of this parallel branch rectifier is PWM modulated and has its harmonic content filtered by inductor L_{RET}.

[8] A "sag to 65%" means that load voltage during the sag is 65% of the load rated voltage value.

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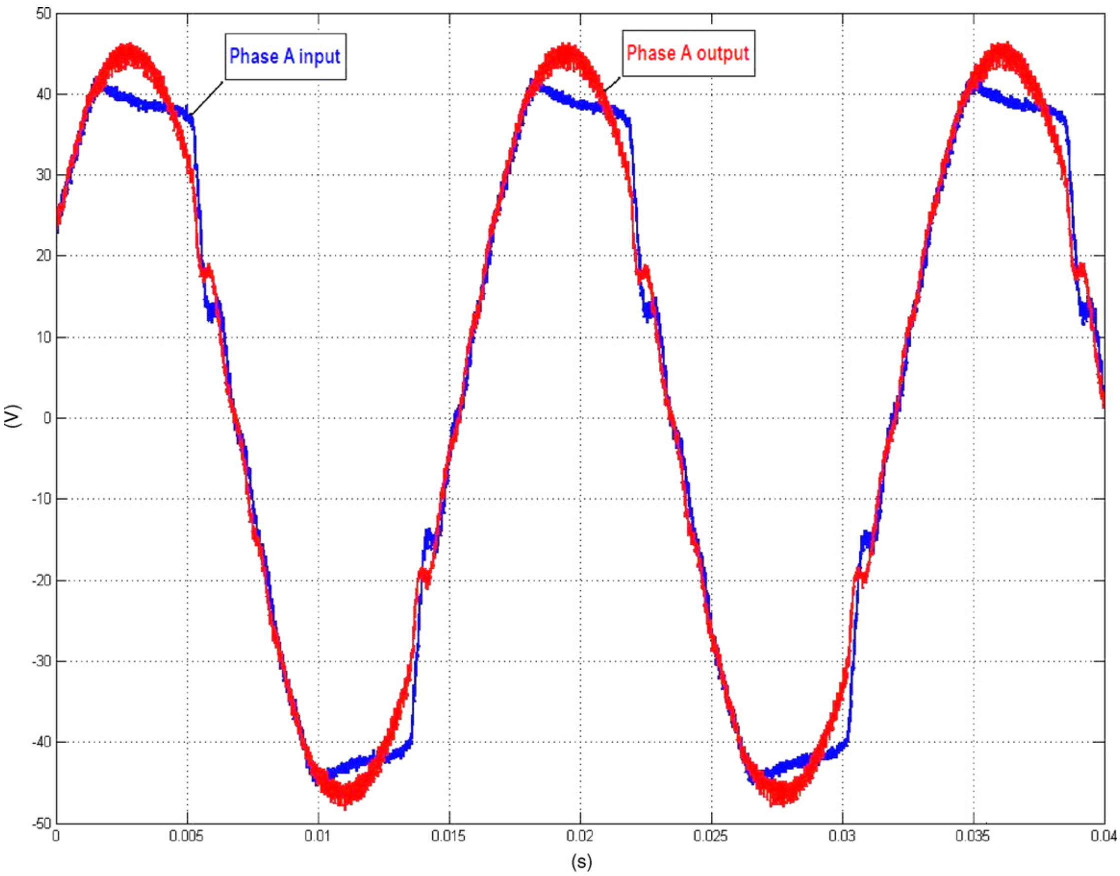

Fig. 3. Voltage harmonics compensation (phase A) on the load. Scales in volts and seconds.

to be used directly as a step to step guide for equipment tests. Therefore, a system compatibility test protocol for power quality mitigation devices should be developed in order to evaluate the equipment, in this case a three-phase DVR device. Such test protocol should cover specific power quality aspects a DVR device is expected to fulfill, such as:

(1) Steady-state and temporary undervoltage and overvoltage;
(2) Steady-state and temporary voltage unbalance;
(3) Voltage sags and swells (single-phase and phase-to-phase, accordingly to a adherent standard);
(4) Single-phasing; and
(5) Dynamic performance, like load step response and response to a sag event.

This list is not meant to be complete, and depends strongly on load (or plant) protection requirements or fulfilling the requirements of a specific standard. The study of load immunity to power quality events is beyond the scope of this work, and it focuses on the characterization of the power quality mitigation device.

The characterization tests highlight most of the common and in some cases the extreme conditions that may occur in typical manufacturing plants such as semiconductor, glass and plastics manufacturing, to name a few. The characterization tests thus bring out the capability of the device to handle extreme conditions in a plant. Additionally, the characterization tests provide information that may help the customer to evaluate the suitability of this device to a particular facility.

The objectives of the characterization tests are multifold, and can be customized for specific equipment. For a DVR device they can cover aspects like:

(1) Performance characterization of the device and verify that it meets the manufacturer's specifications;
(2) Determination of the response time of the DVR to correct sag voltages;
(3) To verify whether the DVR can handle large inrush currents caused by the induction motor loads;
(4) Determining the sag protection envelope of the DVR with industrial load types like AC ice-cube relays[9] and magnetic contactors; and
(5) To uncover any application issues that will be valuable to the end user.

3.3. Experimental test performed at EPRI – Knoxville

3.3.1. Brief description of equipment and applied tests

In March 2008, the micro-DVR was subjected to extensive characterization tests at the Electric Power Research Institute (EPRI), Knoxville, TN, USA. The basic experimental setup is shown in Fig. 5.

Even though the equipment is a research prototype, it was tested at EPRI as an ordinary commercial voltage disturbance mitigation device, following the SEMI F47-0706 standard [17], shown in Table 1 and Fig. 6.

EPRI's Porto-Sag voltage sag/swell generator device [23] was used to apply voltage sags and swells. Mass data acquisition was made using Porto-Sag connected computer and Nicolet Vision XP Data Acquisition System [24]. For these particular tests, the amount of generated raw data was greater than 12 GB.

[9] In this paper an "AC ice-cube relay" is an AC coil relay, usually housed in clear plastic with an ice cube appearance.

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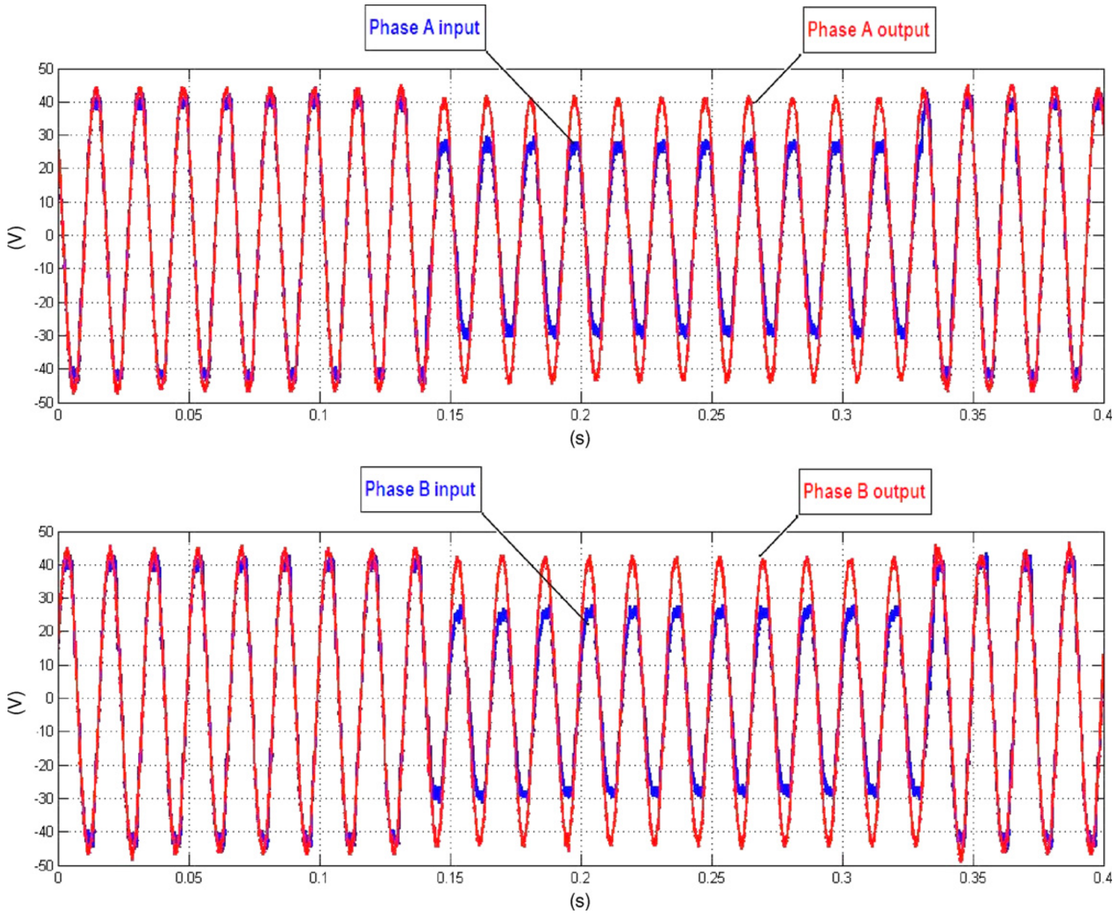

Fig. 4. Three-phase sag to 65% compensation (showing only phases A and B) with resistive load $R = 22\ \Omega$. Scales in volts and seconds.

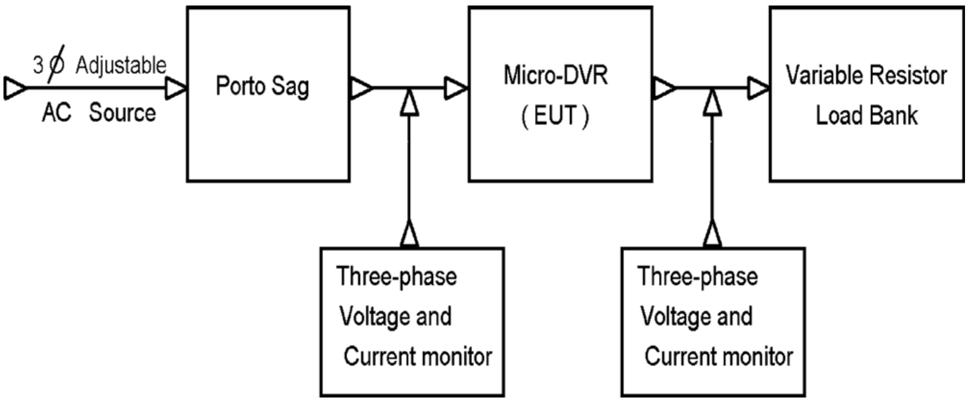

Fig. 5. Experimental setup for sags and swell tests.

Typical low power sag-sensitive devices, such as control relays, were also tested, using the setup of Fig. 6, by stepping-up the phase voltage from the original 31 V to 120 V and applying it to the industrial load bank (ILB), a device also developed by EPRI [25]. The ILB is a permanent fixture that allows engineers to demonstrate the voltage-sag susceptibility of typical control components such as relays, contactors, and power supplies and to characterize the ability of single-phase power conditioners to improve immunity of these loads. The ILB is used to create a real-life loading environment for power-conditioning devices that will be used to demonstrate protection and immunity improvements, and serves as an excellent test platform for evaluating the effectiveness of various power quality mitigation devices.

The following tests were applied on the micro-DVR.

3.3.1.1. Response to low steady-state input voltage. A combination of the following conditions can contribute to steady-state under voltage. One candidate is increased load on the system, whether it is a single large load, or cumulative effects of multiple loads. A common scenario is the addition of a new load that was not anticipated at the time of power system design. Another cause of low steady-state input voltage is the switching off of capacitor banks, whether intentionally, or by fuse actuation. Malfunctioning of a voltage regulator or load tap-changing transformer can also reduce voltage at the point of utilization for extended periods.

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Table 1
Required voltage sag immunity from SEMI F47-0706 standard.

Sag depth[a]	Duration at 50 Hz	Duration at 60 Hz
50%	10 cycles	12 cycles
70%	25 cycles	30 cycles
80%	50 cycles	60 cycles

[a] Sag depth is expressed in percent of remaining voltage. For example, during a 70% sag on a 200 V nominal system, the voltage is reduced during the sag to 140 V (not 60 V).

3.3.1.2. Response to high steady-state input voltage. A temporary overvoltage can appear for several reasons, including overvoltages generated by the utility and those generated inside a customer facility. A reason for increased input voltage on the utility system might be the malfunctioning of a voltage regulator or load tap-changing transformer. Inside the consumer's premises, power factor correction capacitors may be on-line during light loading, thereby raising the utilization voltage.

3.3.1.3. Response to source voltage unbalance. Voltage unbalance is characterized by unequal magnitudes of the three phase voltages. IEEE Standard 519-1992 [20] indicates that an acceptable steady-state range is from 0.5 to 2%. Some utilities are known to accept a 3% unbalance. Unbalance that exceeds 3% can be problematic for three-phase motors, causing an increase in unbalanced current, which leads to overheating. Unbalanced voltages may typically be caused by the removal of individual capacitor banks for service or failure of a single-phase voltage regulator. Additionally, facilities can contribute to the unbalanced condition by unevenly distributing loads across phases.

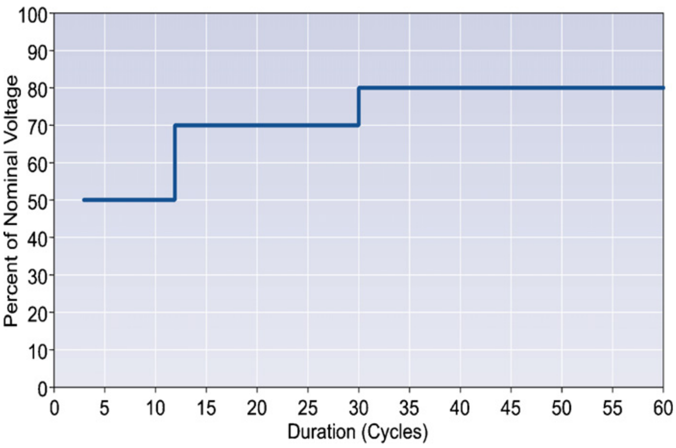

Fig. 6. SEMI F47-0706 standard expected performance envelope.

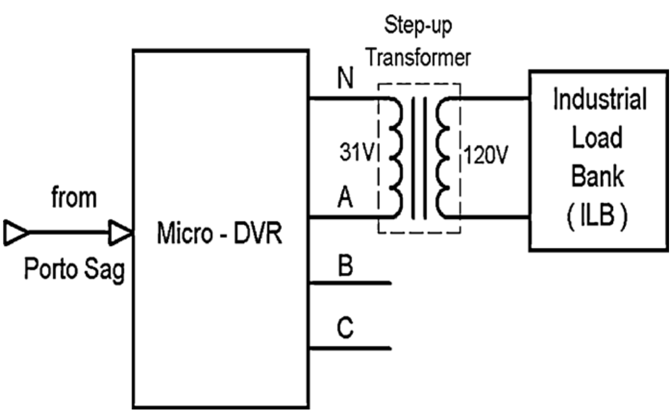

Fig. 7. Experimental setup for sag-sensitive devices, with ILB.

3.3.1.4. Single-phasing. In cases where fuses are not coordinated or designed incorrectly, a single phase-to-ground fault in a facility can leave the other two phases in operation. Three-phase motors can overheat very quickly in this condition. This test consists in disconnecting one of the AC input phases and energizing the device.

3.3.1.5. Voltage regulation. A common condition that may cause temporary undervoltage can be an increased load on the system, be it a single large load or multiple loads or an addition of a new load that was not predictable when the power system was designed. Another cause of temporary low input voltage is the switching off of capacitor banks, whether intentionally or by fuse action. Malfunction of a voltage regulator or load tap-changing transformer can also reduce voltage at the point of utilization for extended periods. A temporary overvoltage can appear for several reasons, including those generated by the utility and those generated inside a customer facility. A reason for increased input voltage on the utility system might be abnormal operation of a voltage regulator or load tap-changing transformer. Inside the consumer's premises, power-factor-correction capacitors may be on-line during light loading, thereby raising the utilization voltage.

3.3.1.6. Response to voltage sags and interruptions. Momentary reductions in line voltage with duration of several cycles or longer may occur during power system faults and when large loads are switched on. Voltage sags are one of the most common and most costly power quality issues in manufacturing environments. When voltage sags are severe enough to interrupt a manufacturing process, the common results are downtime, product waste, and a lengthy cleanup. A momentary increase in line voltage for several cycles can cause certain electronic equipment to respond by shutting down.

3.3.1.7. Response to repetitive voltage sags. Automatic reclosers installed on distribution circuits protect the utility's equipment while providing the convenience of automatically restoring power after a fault. If a fault causes the circuit protection to open, a recloser will attempt to reapply power. In some cases, a fault will clear itself and power can be restored. If not, the recloser will typically make three to four attempts before "locking out" and requiring manual intervention. These repeated operations are often seen as successive voltage sags by many customers.

3.3.1.8. Response to voltage swells. A momentary increase in line voltage for several cycles can cause certain electronic equipment to respond by shutting down. Voltage swells can occur during power system faults or on secondary circuits in ungrounded systems. In radial medium voltage distribution systems, a fault clearing in a branch with a breaker or fuse opening, can lead to a voltage swell in an adjacent branch.

3.3.1.9. Response to step loads. In many automated industrial processes, motors need to be supported by power conditioning equipment in order to produce consistent product during voltage variations. However, not all types of power conditioners can support the large inrush current needed to start the motor.

3.3.1.10. Standby loss and efficiency measurements. Active power measurements in the input and the output of the device under test allow determination of the standby loss and active state efficiency figures.

3.3.1.11. Response time. Response time is defined here as the time taken by the micro-DVR to inject the energy stored in the DC bank through the series branch in order to correct load voltage during voltage sag. This is an important issue for power conditioners

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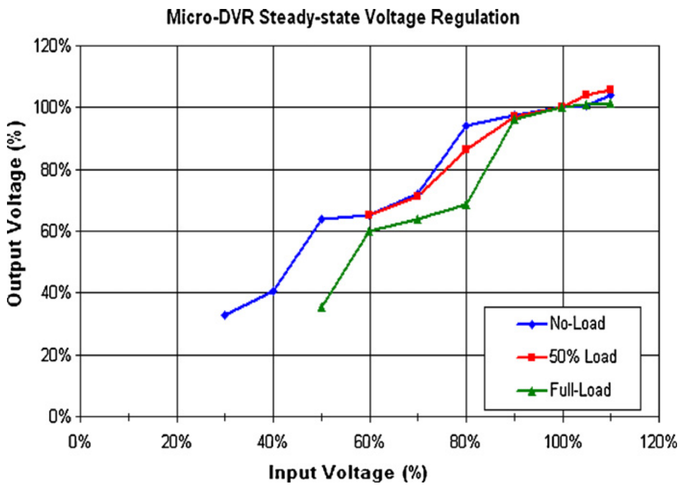

Fig. 8. Steady-state voltage regulation characteristics of the micro-DVR.

because some sensitive loads can trip before the transfer is complete (less than one cycle).

3.3.1.12. Inrush current. Pre and post sag inrush current in a DVR device is due to the (re)charge of its energy storage capacitor bank. During the sag part of the energy can be provided by the capacitor bank, and the other part can come from the AC mains, through the parallel branch.

3.4. Tests results with comments

All results with no abnormalities reported indicate that the ILB was protected by the micro-DVR, meaning, no load in the ILB was interrupted by the sag/swell event, mainly the most sensitive ones, like the AC ice-cube relays.

3.4.1. Response to low steady-state input voltage

In this test, with 0% (no load), 50%, 100% loads, the applied voltage to the micro-DVR was reduced to 85% of the nominal value. No abnormalities were reported.

3.4.2. Response to high steady-state input voltage

In this test, with no load, 50%, 100% loads, the applied voltage to the micro-DVR was increased up to 110% of nominal. No abnormalities were reported.

3.4.3. Response to source voltage unbalance

This test was covered under steady-state under voltage input test, because the AC source itself was not balanced. The measured unbalance was dynamically changing within 5%. Measured output voltage unbalance was corrected to less than 1%.

3.4.4. Single-phasing

An interesting result was obtained: voltage feeding back to the missing (disconnected) input. However, this is a normal condition for many electrical equipment, e.g. AC induction motors. The explanation is that the PWM rectifier (Fig. 2) feeds back a three-phase voltage, supplying for the missing phase.

3.4.5. Voltage regulation

The micro-DVR regulation was tested during sags and swells, as well as over voltages and under voltages. Fig. 8 shows the sag/swell and steady-state voltage regulation characteristics of micro-DVR. The micro-DVR was able to provide continuous voltage regulation of ±5% when the input supply voltage was within −10%, as per its specification. Also in this case the PWM rectifier regulates the DC link voltage (V_{DC}) within its specified voltage range.

3.4.6. Response to voltage sags and interruptions

Using 0–50–100% resistive loads, one, two and three phase sags and swells with 115–80–70–60–50–40% depth and 5–12–30–60 cycles[10] duration were applied. The micro-DVR withstood the required voltage sag immunity of SEMI F47-0706 standard [17] for one-phase and two-phase sags, and failed the three-phase 50% with 12 cycles duration sag (e.g. Fig. 10 shows a 10 cycles 50% sag with unsuccessful correction). For longer and deeper sag events, when DC link voltage dropped below a preset value, an expected bypass behavior occurred.

The following figures show waveforms of experimental results. Acquired data from the Nicolet Vision XP was saved in csv files[11] and processed with MATLAB software. Fig. 9 shows the response time for the sag event which is less than half cycle during a successful sag correction by micro-DVR. Fig. 10 shows the decline in the DC link voltage during a longer voltage sag event. It can be seen that when the DC link voltage reached a minimum voltage threshold value, micro-DVR controller bypassed the series injection voltage transformers with electrical relay contacts (see Fig. 2), thus effectively stopping the micro-DVR series voltage injection action.

The same effect of Fig. 10 can be seen in Fig. 11 with prolonged sag (three-phase, 50% sag, 180 cycles). In Fig. 11 the micro-DVR stops injecting series voltages as DC link voltage drops below the threshold value, but reconnects and resumes series voltage injection as the capacitor bank C recovers to a certain amount. As the sag event is long, this process continues repeating.

Fig. 12 shows the application of a three-phase 80% sag with 60 cycles duration and the industrial load bank (ILB) connected to phase A, and with phases B and C unloaded (see Fig. 7).

Fig. 13 shows a phase interruption (application of null voltage only to phase A) during 12 cycles. The affected phase at output is corrected during this fault because it is fed through the DC link by the parallel converter (see Fig. 2).

3.4.7. Response to repetitive voltage sags

In these tests, three-phase sags of 6 cycles duration, down to 40% and 60%, were repeated at 5 s intervals and 10 s intervals, with the ILB load used on phase A, and 50% resistive load on phases B and C. No abnormalities were reported, and the micro-DVR successfully applied nominal voltage to the ILB load, protecting it against the repetitive voltage sags.

3.4.8. Response to voltage swells

Swells of 115% and up to 60 cycles were corrected by the micro-DVR with no abnormalities. It should be noticed that this test, as well as high steady-state input voltage test, are chronologically the last ones to be performed in a characterization test, as they involve a potential destructive behavior on the tested device. In the micro-DVR case, excess energy from the swell is diverted from the series injection transformer to the DC link and back to AC side through the PWM rectifier.

3.4.9. Response to step loads

Response for 0% (no load), 50%, 100% loads have shown a response time shorter than half AC cycle.

[10] 60 Hz mains frequency, 220 V three-phase feeding, with neutral wire available.
[11] Comma separated values file.

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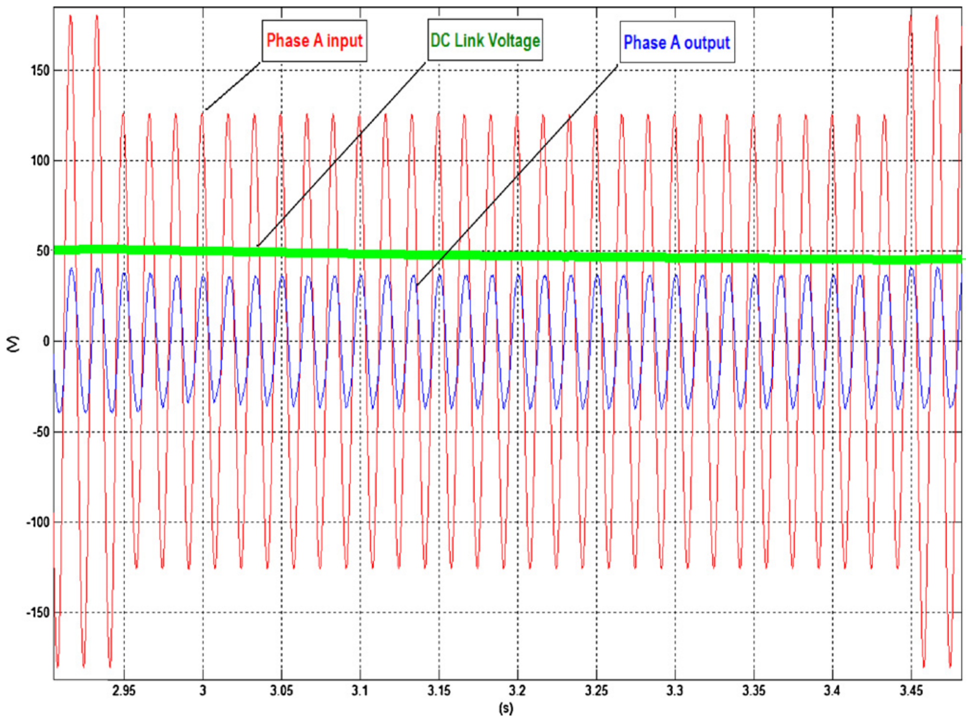

Fig. 9. Experimental three-phase sag with 70% depth and 30 cycles duration with successful correction (100% resistive load), showing phase A input (red), phase A output (blue) and DC link voltage (green). Scales in volts and seconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

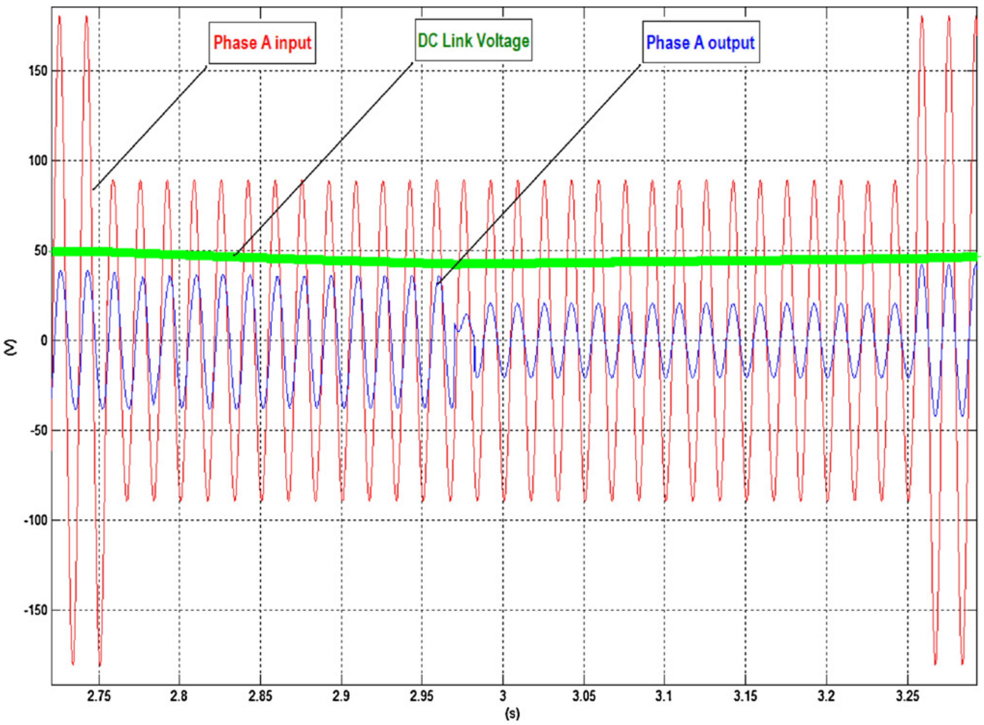

Fig. 10. Experimental three-phase sag with 50% depth and 30 cycles duration with unsuccessful correction (100% resistive load), showing phase A input (red), phase A output (blue) and DC link voltage (green). Scales in volts and seconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4.10. Standby loss and efficiency measurements

Table 2 shows standby loss and efficiency figures for 0%, 50% and 100% load power. Since the micro-DVR is a development platform prototype, the system is optimized for safety but not for efficiency neither performance. Such low efficiency figures can be improved for production models.

3.4.11. Response time

The response time of the micro-DVR was found to be shorter than half cycle (less than 4 ms in most cases). Response time was determined by zooming the waveforms obtained from the sag events, for instances, Figs. 9 and 10, at the sag moment.

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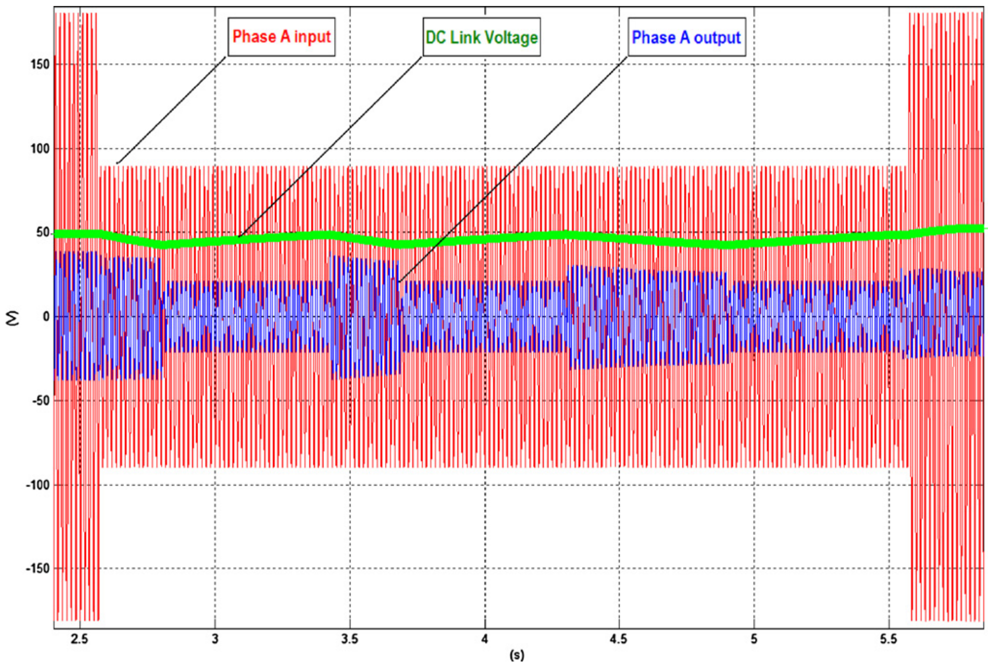

Fig. 11. Experimental three-phase sag with 50% depth and 180 cycles duration with unsuccessful correction (100% resistive load), showing phase A input (red), phase A output (blue) and DC link voltage (green). Scales in volts and seconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Standby loss and efficiency measurements.

Load	Input power	Output power	Efficiency (P_{out}/P_{in})
0%	96.1 W	0 W	–
50%	250.1 W	103.7 W	41.5%
100%	403.2 W	225.4 W	55.9%

3.4.12. Inrush current

Data from voltage sag tests can be used to measure post-sag and pre-sag inrush of the power quality mitigation device itself. The micro-DVR inrush current typically increases with depth and duration of the sag, mainly due to the DC capacitor bank recharge process (from both the micro-DVR and the DC power sources

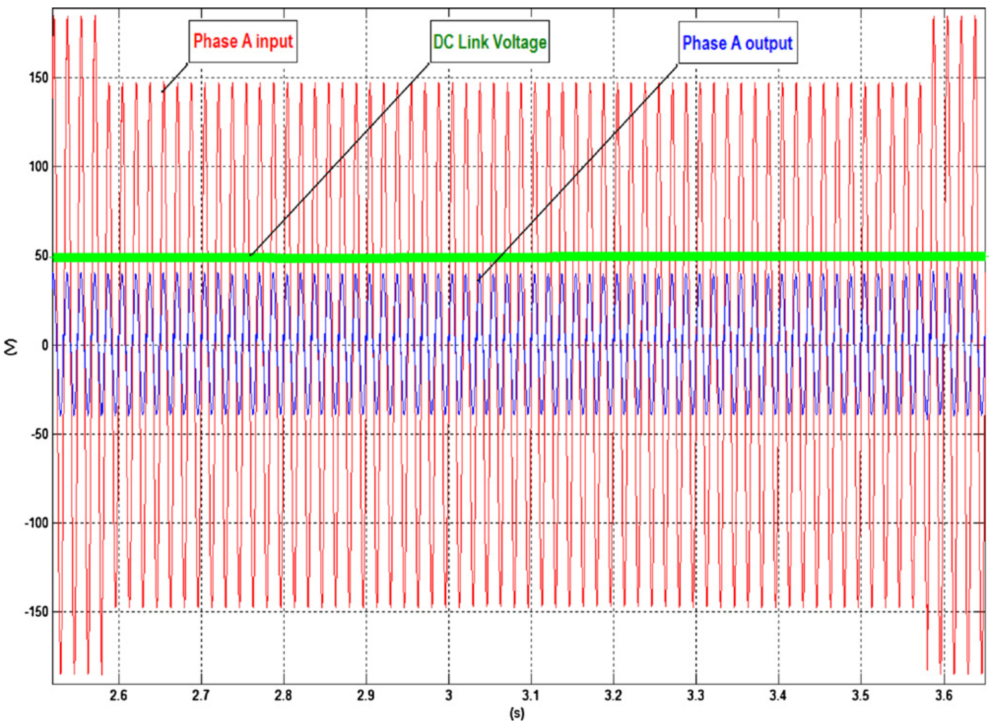

Fig. 12. Experimental three-phase sag with 80% depth and 60 cycles duration with successful correction (ILB applied only in phase A), showing phase A input (red), phase A output (blue) and DC link voltage (green). Scales in volts and seconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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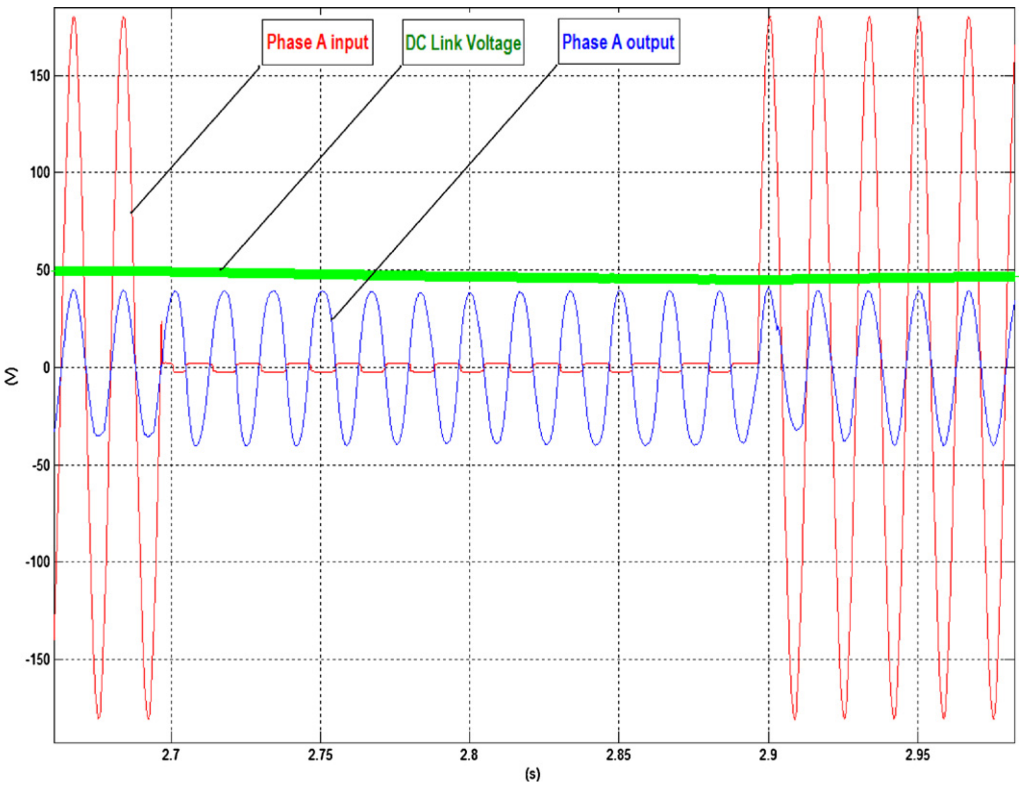

Fig. 13. Experimental one-phase interruption with 0% depth and 12 cycles duration with successful correction (100% resistive load), showing phase A input (red), phase A output (blue) and DC link voltage (green). Scales in volts and seconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

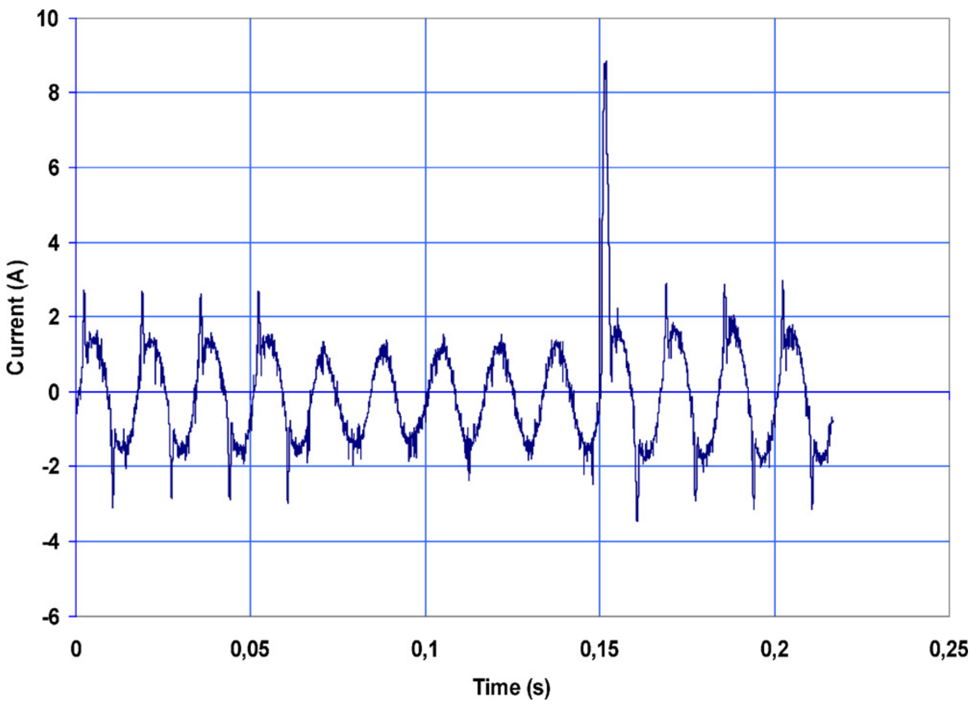

Fig. 14. Typical inrush current waveform of micro-DVR during three phase voltage sag at 50% depth, 5 cycles. Scales in amperes and seconds.

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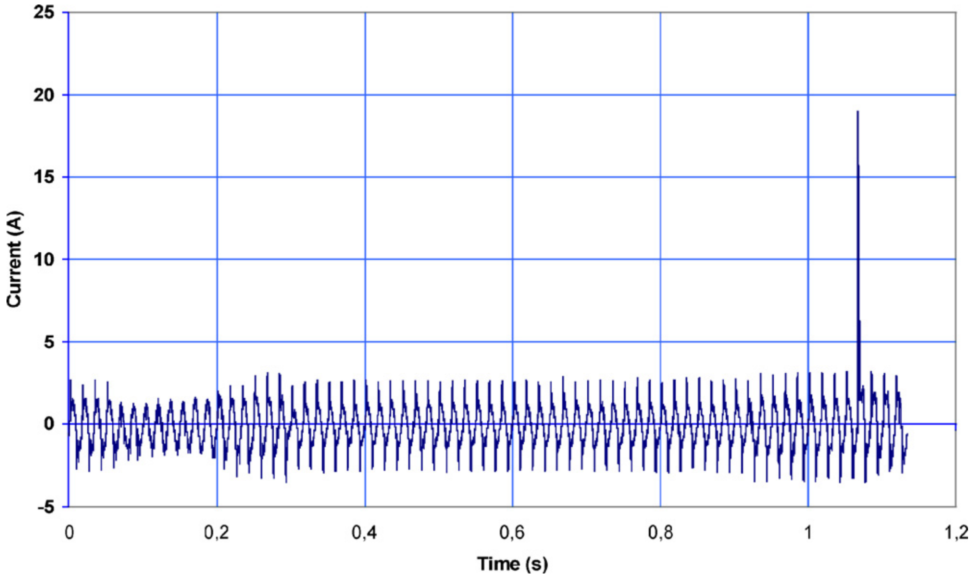

Fig. 15. Typical inrush current waveform of micro-DVR during three phase voltage sag at 50% depth, 60 cycles. Scales in amperes and seconds.

within the ILB). The inrush current of the completely depleted DC capacitor bank during initial energization is limited by resistors (resistors R_{RET} of Fig. 2), but these resistors are bypassed under normal operation, and DC capacitor bank is recharged after the sag in a uncontrolled fashion through the reverse conducting diodes of the IGBTs[12] of the parallel branch PWM rectifier (see Fig. 2). Figs. 14 and 15 show typical inrush current waveforms recorded on the input of micro-DVR due to voltage sag, both taken with the Nicolet Vision XP Data Acquisition System [24]. It must be notice that some performed tests can be easily checked against the applied standard, e.g. response to voltage sags. Other tests, like inrush current and efficiency figures, are not directly referred in such standard, and these results must be considered comparing to a particular customer requirement the device should satisfy.

Test results help characterizing the micro-DVR and its limitations. For instance, it did not succeeded in compensating a three-phase 50% with 12 cycles duration sag, violating SEMI F47-0706 requirements (see Fig. 10). If it were a commercial DVR, the manufacturer would need to increase energy storage, by adding more capacitors to the DC bank for instance. Notice that even though the micro-DVR has the capability of filtering AC voltage harmonics at the load side (see Fig. 3) voltage filtering performance was not measured, as SEMI F47-0706 does not require it. In order to analyze voltage harmonics, one should insure high enough voltage acquisition rate in order to apply adequate harmonic analysis (by using fast Fourier transform in the MATLAB environment, for instance), Notice that harmonics analysis should be done in steady state conditions, avoiding transient state (during sags and swells) and choosing the adequate time window (integer value of the fundamental AC voltage period). Another issue worth of investigation is the post-sag inrush current. It is addressed in the SEMI F47-0706 without numerical values, discussing protection coordination and equipment immunity due to inrush current effects.

4. Conclusions

This work presents a case study on technology assessment for power quality mitigation devices. Specifically, a system compatibility test protocol for power quality mitigation devices was developed by EPRI in order to evaluate the functionality of three-phase voltage restoration devices. The tests were applied in a development platform with reduced power for DVR (dynamic voltage restorer), the micro-DVR. The choice for a development platform instead of a commercial equipment allowed immediate assessment of test results as most of the characteristics of the equipment were known or easily obtainable. The test results can be scaled upwards to the full power functioning DVR models.

Tests methodology and results were presented and discussed, based on test protocol and voltage disturbance standards.

Acknowledgements

The authors gratefully acknowledge the contributions of Chakphed Madtharad and Kritsada Kleebmek from Thailand's Provincial Electricity Authority (PEA) in the experimental setup and data acquisition activities at EPRI.

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