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A practical disturbance generator to test performances of various power quality mitigation devices

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Abstract: In this paper, a practical thyristor-based 3-phase sag/swell/outage generator (disturbance generator) is designed to test various power quality mitigation devices (PQMDs), such as solid state transfer switch (SSTS), static voltage compensator (SVC), and uninterruptible power supply. The latest technological disturbance generators (DGs) and the proposed DG are comprehensively discussed and compared with focus on usefulness, economic aspects, and simplicity. The proposed DG is used for experimentally generating different fault conditions and testing a SSTS. The comparisons and analyses show that the proposed DG is an optimum and simple solution to generate sag, swell, unbalance, overvoltage, undervoltage, and outage to test PQMDs.

Key words: Power quality, disturbance generator, power quality mitigation device, voltage sag, voltage swell, outage

1. Introduction

The power quality (PQ) requirement is one of the most important issues for electrical utilities and consumers [1]. The equipment used in modern industrial and commercial plants (process controllers, programmable logic controllers, adjustable speed drives, robotics, computers, etc.) is actually becoming more sensitive to PQ disturbances such as outages, voltage sags [1], voltage swells, harmonics [2], and transients as the complexity of the equipment increases [3]. To reduce the effect of PQ disturbances, PQ mitigation devices (PQMDs) can be applied to the systems. PQMDs are a concept based on the application of power electronic controllers in distribution systems to supply reliable power [4–6]. However, disturbance generators (DGs) are necessary to test the performance of the PQMDs before the installation of the devices in the plants. Single or 3-phase voltage sags, swells, outages, harmonics, transients, phase shifts, and flickers can be generated using various DGs having different circuit topologies.

Most of the loads in industry are connected in a 3-phase connection. The methods examined in this paper are used to generate 3-phase PQ disturbances. A high-power sag/swell generator was proposed in [7]. The thyristor-controlled reactor (TCR)-based topology was used in [7] and the system is composed of a reactor, TCR system, inductor–capacitor (LC) harmonic filter, step-down transformer, and step-up transformer. The high-power sag and swell voltage generator for the evaluation and testing of PQMDs was proposed in [8]. The inverter-based topology in [8] is too expensive to use for general purposes because many components, such as a

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rectifier unit, inverter unit, harmonic filter, series transformer, parallel transformer, and switch gear, are used. In [3], Nho et al. used a series transformer, backup silicon-controlled rectifier (SCR) switches, and an auto transformer for each phase. Their study introduced a sag, swell, outage, flicker, and harmonic generator. The auto transformer-based topology with thyristors has limitations in getting the different output voltage values in [3]. Naidoo and Pillay [9] used a transformer, solid state relay switch, and PC. This DG can generate sag, swell, and outage but it has limitations in getting flexible output voltage values due the limited and constant-value secondary outputs. A voltage quality DG composed of a pulse width modulation (PWM) rectifier and cascaded H-bridge inverter was proposed in [10], where a voltage sag, voltage swell, and harmonic generator were also introduced. In [11], Yang et al. proposed a current quality DG. The generator is divided into a fundamental power module and harmonic power module. The fundamental power module can generate current at power frequency and below power frequency. The harmonic power module can generate various harmonic current disturbances. Each power module is composed of a single-phase PWM rectifier unit and an H-bridge multilevel inverter. The generator evaluated in [12] generates harmonic current, adjustable negative sequence current, fluctuant current, and the adjustable power factor. The H-bridge cascade structure is used to generate the various current disturbances in fundamental frequency or less-fundamental frequency.

In this paper, a practical and cost-effective 3-phase sag/swell/outage generator, composed of a variable transformer, thyristors, and time relays, is presented. The ability of the proposed DG is also compared with the other DGs presented in the literature. The proposed DG can produce the voltage sag, swell, and outage at any time and at the desired amplitude. These PQ disturbances are the most severe disturbances and these are relatively enough to test the performances of a solid state transfer switch (SSTS), static voltage compensator (SVC), and uninterruptible power supply (UPS). The disturbance generating capability of the proposed DG is verified with experimental results and the proposed GD is used for testing a SSTS, also called a static transfer switch.

This paper is therefore organized as follows: after this introductory section, the conventional methods for the generation of PQ disturbances are presented in Section 2. The operation principles of the proposed DG are given in Section 3. The economic and usefulness analyses of the presented methods are explained in Section 4. The experimental results for the proposed method are presented in Section 5. Finally, the main points, advantages, disadvantages, and significant results of the study are summarized in the conclusion.

2. Available methods for generation of power quality disturbances

The available DGs can be grouped into 3 types, namely the power converter type [8], auto transformer switch type [3,9], and TCR system type [7]. An overview of the available methods is clearly summarized in the following subsections.

2.1. Power converter type

Typical power disturbances such as voltage sag, voltage swell, outage, over voltage, under voltage, and voltage flicker can be generated using a DG composed of an energy storage DC capacitor, series inverter made of insulated gate bipolar transistors, SCR thyristors, series transformer, LC filter, rectifier, and clamp circuit. Moreover, it can generate the distorted voltage waveforms and phase jumping by controlling the series inverter. Figure 1 shows the circuit diagram of such a DG used in [8].

The topology of the DG is similar to that of the dynamic voltage restorer [13], except for the power ratings of the parallel transformer and the rectifier. During voltage sag generation, energy is absorbed by the series inverter and dissipated through the voltage clamp circuit. On the other hand, during voltage swell generation, DC energy is supplied through the parallel transformer and rectifier. The bypass switch consisting of antiparallel thyristors is used to connect the voltage source (V_A, V_B, and V_C) to the load unless the fault condition is presented.

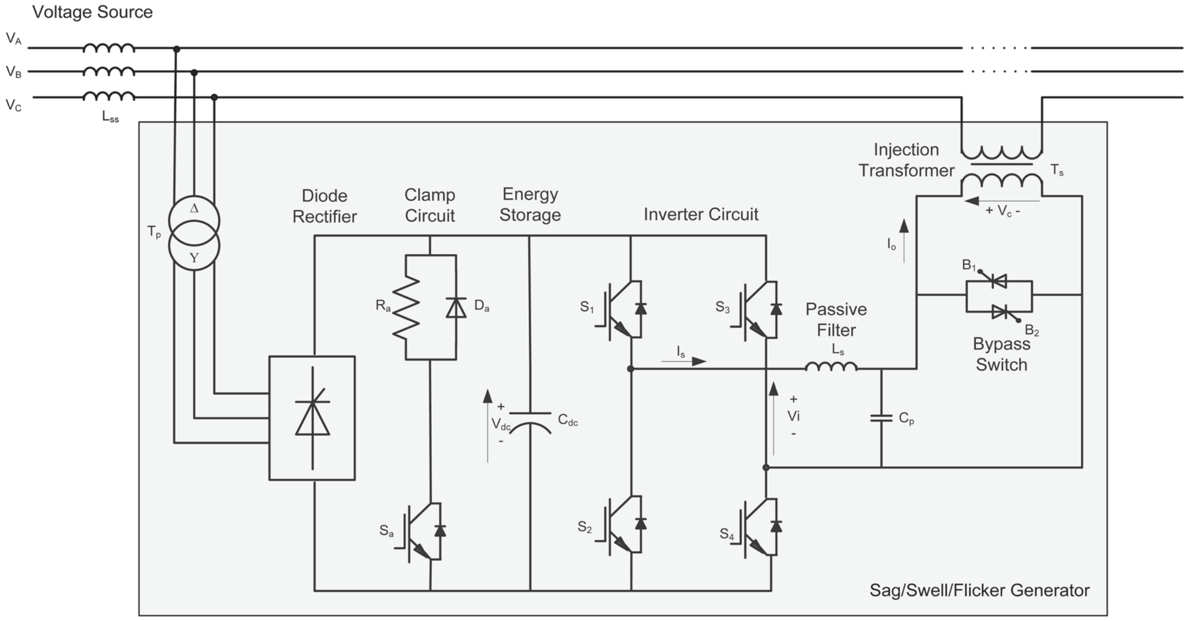

Figure 1. The circuit diagram of the DG used in [8].

2.2. Auto transformer switch type using thyristors

A different sag-swell generator for the test of custom power devices is described in [3]. Voltage sag, voltage swell, outage, harmonic distortion, notches, and voltage unbalance can be generated. Figure 2 shows this single-phase DG using an auto transformer, series transformer, and SCR thyristors.

In Figure 2, the source voltage V_s is constant. To produce a disturbed voltage V_o, a series transformer T_d is inserted between the negative grids of the source voltage and the output terminal. The secondary voltage of the transformer (V_d) is determined by multiplying the turn ratio of the transformer and the secondary voltage of the auto transformer (V_t). If the moving contact point is in the I-region, voltage V_d is positive, which is added to the source voltage, resulting in a voltage swell of output voltage V_o. Similarly, the voltage sag can be obtained by moving the contact point to the II-region of the auto transformer. The outage is also generated by adjusting the magnitude of the voltage sag to 100% of the source voltage.

The controller triggers S_1 and S_2 to connect or disconnect one of the tap winding sections into the circuit. The antiparallel thyristors S_{B1} and S_{B2} are used as bypass switches that connect the auto transformer output to the load unless the fault condition is presented [3].

2.3. Auto transformer switch type using solid-state relays

Figure 3 shows the single-phase DG using an auto transformer, solid state relays, and PC and digital signal processor (DSP) controllers in [9]. The voltage sag and swell can be generated with this DG. It has taps that can be set from 40 V to 400 V in steps of 40 V that generate an output voltage between 0% and 160% of the nominal voltage.

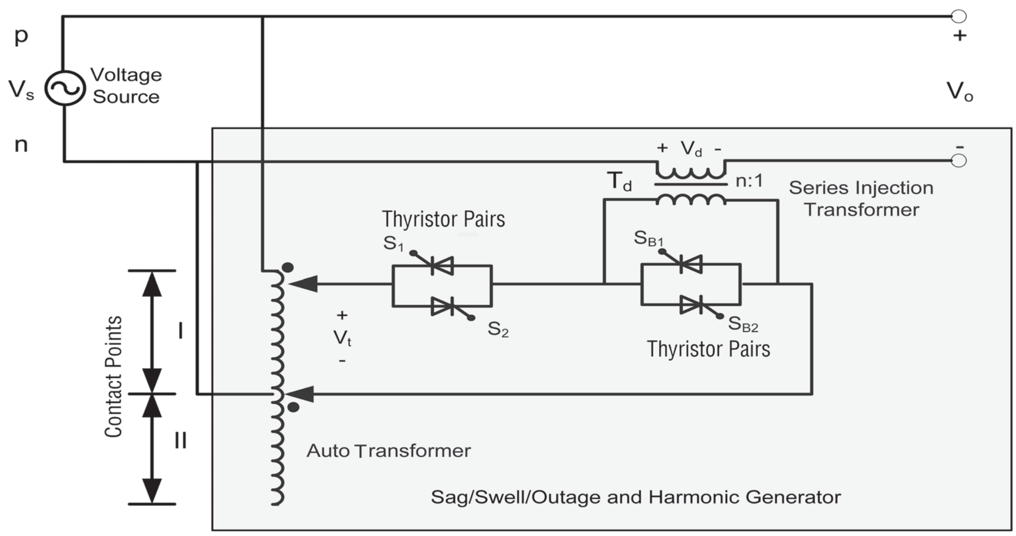

Figure 2. The circuit diagram of the DG used in [3].

A transformer is used with 2 output voltages. The first output is set to 100% of the rated voltage. The second output is set to the required sag magnitude value. It has taps that can be set from 40 V to 400 V in steps of 40 V. The DSP is used to log data and switch solid state relays very quickly between the 2 outputs to obtain the desired sag magnitude and duration. When testing the performance for the rate of change, a cascaded configuration is used.

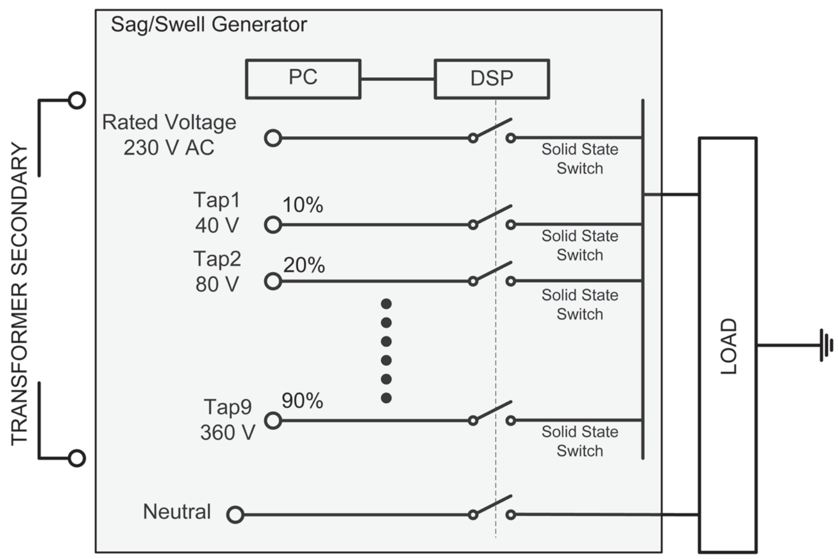

Figure 3. The circuit diagram of the DG used in [9].

2.4. TCR system type

Typical power disturbances such as sag, swell, outage, under voltage, over voltage, and harmonic distortion can be generated using the DG composed of a line reactor, TCR system, LC harmonic filter, step-up transformer, and step-down transformer in [7]. Figure 4 shows the sag/swell generator with a TCR used in [7].

Voltage sag and under voltage can be generated using the voltage drop across a reactor X_n when the thyristors in the TCRs are turned on after switch SW_1 is closed, while its magnitude and durations can be controlled by the firing angle of 2 TCRs. In the case of the swell and the over voltage generation, the output of the step-up transformer is connected to the TCRs through switch SW_2 and the step-up voltage is regulated by 2 TCRs to obtain a nominal voltage level. At any given instant, if the firing angle of the 2 TCRs is retarded, then the swell voltage or the over voltage disturbance can be obtained.

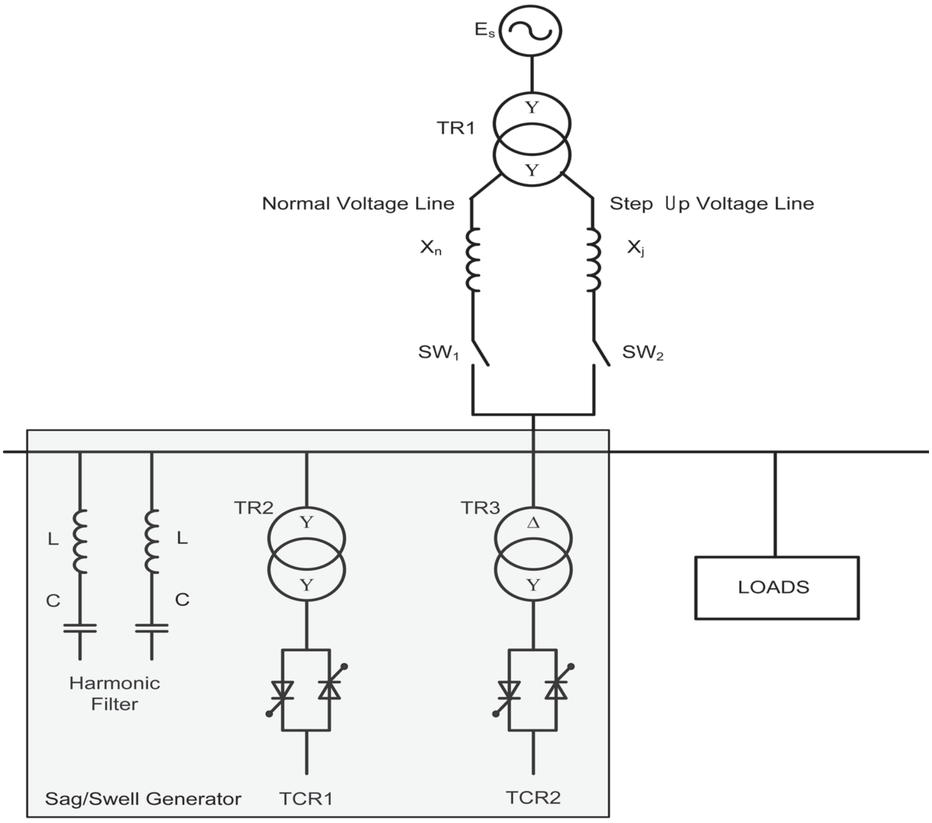

Figure 4. The circuit diagram of the DG used in [7].

3. The proposed DG

Typical power disturbances such as sag, swell, unbalance, unbalanced voltage, over voltage, and under voltage are easily generated using the proposed DG, consisting of a variable transformer, SCR thyristor pairs, and time relay. Figure 5 shows the circuit diagram of the proposed method.

The normally closed (S_a, S_b, and S_c) and normally open ($\overline{S}_a$, $\overline{S}_b$, and $\overline{S}_c$) contacts of the time relays (TimerA, TimerB, and TimerC) are used to trigger the thyristor pairs at any instance of time. Normally, the loads are fed by the main voltage source and the source side thyristor pairs are triggered by the normally closed contacts of timers. The voltage level of the disturbance is adjusted by changing the tap of the variable transformer before the voltage sag, swell, or outage generation is desired, and then millisecond-based time relays are adjusted and energized. During this period, the loads are fed by the variable transformer and the variable transformer side thyristor pairs are triggered by the normally open contacts of the timers.

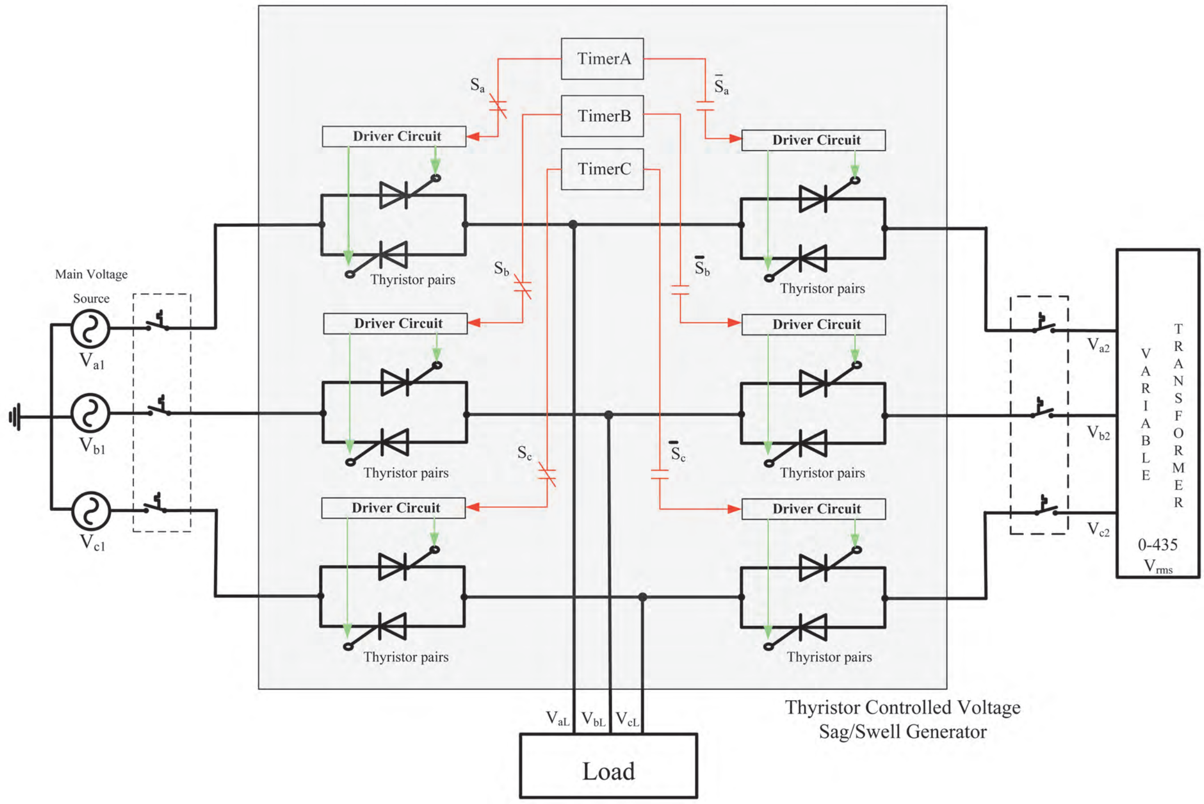

Figure 5. The circuit diagram of the proposed method.

The logical impressions of the load voltages for each phase are given below.

$$V_{aL} = S_a.V_{a1} + \bar{S}_a V_{a2} \tag{1}$$

$$V_{bL} = S_b.V_{b1} + \bar{S}_b V_{b2} \tag{2}$$

$$V_{cL} = S_c.V_{c1} + \bar{S}_c V_{c2} \tag{3}$$

Table 1 shows the contact states of the time relays for different kinds of faults. The single-phase to neutral voltage, having an amplitude of 220 V_{rms}, is equal to 1 per unit (pu).

The variable transformers allow for flexible output voltage values, and thus the balanced and unbalanced faults are easily generated.

4. Comparison and discussion of the presented methods

The presented methods are compared on the basis of usefulness, simplicity, and economic aspects. The optimum selection of DGs is achieved using these criteria.

Table 1. Contact states of the time relays for different kinds of faults.

Disturbance type	States of contacts							
	S_a	$\bar{S}_a$	S_b	$\bar{S}_b$	S_c	$\bar{S}_c$	Phase voltages of the main source (pu)	Phase voltages of the variable transformer (pu)
Normal conditions	1	0	1	0	1	0	1	Any value
40% sag on phase A	0	1	1	0	1	0	1	0.6
30% sag on all of the phases	0	1	0	1	0	1	1	0.7
Power interruption	0	1	0	1	0	1	1	0.0
15% swell on phase B and phase C	1	0	0	1	0	1	1	1.15

4.1. Comparison of usefulness

As concluded from the available methods, there are 3 common types of DGs: the auto transformer switch type [3,9], power converter type [8], and TCR system type [7]. In this section, the characteristics, advantages, and drawbacks of each method are discussed with focus on their usefulness and simplicity.

First, the users should clearly specify which PQMD will be tested or which PQ disturbances will be generated. Table 2 shows the most common PQ disturbances and the disturbance generation ability of the DGs to perform these disturbances.

The auto transformer switch type of DG is usually realized as a combination of an auto transformer and the appropriate switching devices. The different voltage outputs are generated by switching the output contacts from one step to another. This method has good features of generating harmonics by simply controlling the firing angles of the thyristor pairs. The main drawbacks of the method are that all of the nonconducting thyristor pairs connected to the unselected taps dissipate power due to their leakage current and the increased number of thyristor pairs connected to the taps. It has a complex structure with signal processor control.

Table 2. The disturbance generation abilities of the methods.

PQ disturbances	Available methods				
	Method in 2.1	Method in 2.2	Method in 2.3	Method in 2.4	Proposed method
Sag	x	x	x	x	x
Swell	x	x	x	x	x
Harmonic	x	x		x	
Flicker	x				
Outage	x	x			x
Notch		x			
Unbalance voltage		x			x
Over voltage	x			x	x
Under voltage	x			x	x

The power converter-based type of DG usually uses power electronic converters and energy storage units. This configuration is more appropriate than the auto transformer switch type because it produces more precise control of the disturbances. The main disadvantage of this method is having a very large number of power electronic converters, which requires high initial costs and a complex control algorithm.

The TCR-based type is usually realized as a combination of transformers, TCRs, and reactors. The different voltage outputs are generated by firing the TCR at different angles. The principal disadvantages of this configuration are the generation of low frequency harmonic current components and higher losses when working in the inductive region [14]. This method also has a large number of input/output components.

The variable transformer switch type is proposed in this study and it is realized practically as a combination of a variable transformer, thyristor switching devices, and a millisecond-ranged time relay. This structure can be set up practically. The main source is used for the prefault voltage and the variable transformer is used at fault conditions. The voltage magnitude of the variable transformer is adjusted manually for different fault conditions. This provides the different output voltages with more precision using the smallest number of thyristor pairs. The proposed method is similar to method 3 (auto transformer switch type using solid-state relays); however, the proposed method can also generate outage, unbalance voltage, over voltage, and under voltage. Despite the advantages listed above, the proposed method cannot generate harmonics.

4.2. Economical comparison

This section presents the comparison of the costs of the previously presented DGs. The cost information is obtained from a variety of sources including sales companies [15–17] and surveys. The cost is given as a kV base for each component of the devices. The prices of the components required to set up a 10 kVA DG, which is enough to build a laboratory-scale prototype, are given in Table 3 for economic comparison of the presented methods.

The method in Section 2.4 is the most expensive DG. The method in 2.3 is the cheapest solution to generate voltage sag and swell. The PC and DSP are used in methods 2.1, 2.3, and 2.4 to implement the control algorithm and generate the gate signals.

Table 3. Comparison of the component prices.

Components	Approximate cost ($)	Number of components used in the DGs				
		Method in 2.1	Method in 2.2	Method in 2.3	Method in 2.4	Proposed method
3-phase auto transformer	625	-	1	1	-	-
3-phase variable transformer	1400	-	-	-	-	1
3-phase rectifier	550	1	-	-	-	-
1-phase inverter	380	3	-	-	-	-
1-phase series transformer	425	3	3	-	-	-
3-phase step-down transformer	1950	1	-	-	2	-
3-phase step-up transformer	1950	-	-	-	1	-
SCR thyristor pairs	33	3	6	-	6	6
SCR driver circuit	250	3	6	-	6	6
Solid state relay	9	-	-	11	-	-
Time relay	30	-	-	-	-	3
DC link capacitor	75	1	-	-	-	-
LC filter	240	3	-	-	6	-
Line reactor	220	-	-	-	6	-
Current transducer	28	3	-	-	-	-
Voltage transducer	55	3	-	-	-	-
PC	800	1	-	1	1	-
DSP controller	380	1	-	1	1	-
Total Cost ($)		7988	3598	1904	11,488	3088

4.3. Optimum selection of the DGs

By comparing the capability of producing different types of PQ disturbances, the ease of setup, and initial setup costs for each method, one or more alternatives may be eliminated from consideration. Figure 6 shows the comparison of all methods for the disturbance generation capability, ease of setup, and initial setup cost.

The optimum selection procedure ends when only one alternative remains that satisfies the users' demand to test the PQMD. The present investigation shows that the proposed method is a more convenient method to generate the most common PQ disturbances, such as voltage sag, voltage swell, and outage, being cost-effective and easy to set up.

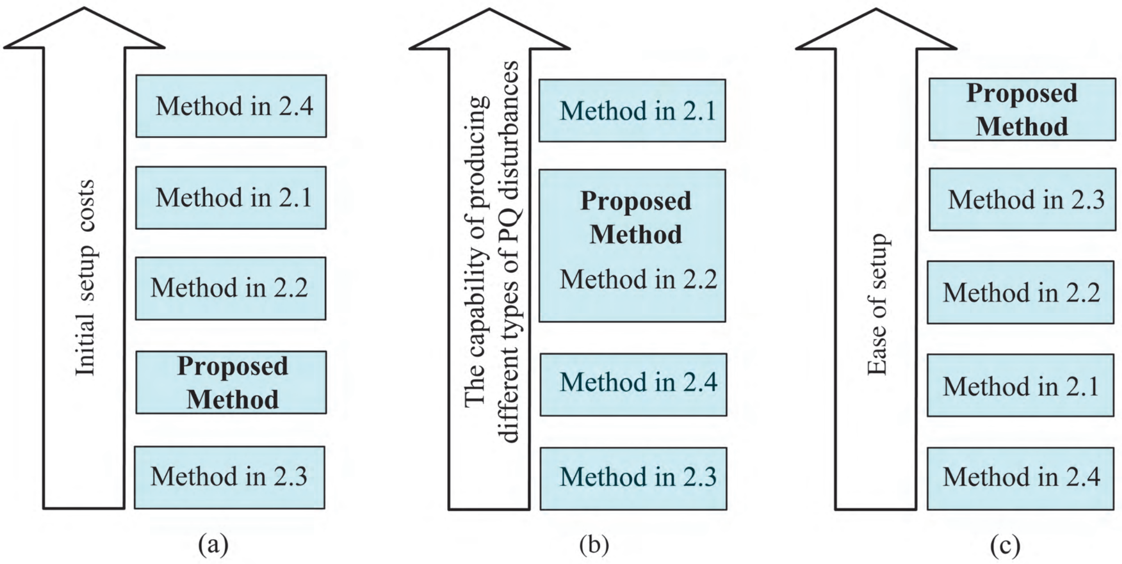

Figure 6. The selection of DGs according to a) initial setup costs of all of the methods, b) ease of setup, and c) capability of the DGs.

5. Experimental setup and results of the proposed method

The experimental setup system composed of thyristor modules, driver modules, and time relays is shown in Figure 7.

Semikron APTT-841M drivers are used for triggering the antiparallel-connected thyristors. This module requires an external +12 V_{cc}/250 mA power supply. The thyristors can be triggered using an external 12 V_{cc} voltage supply connected between 0 V and the trigger.

The specifications of the proposed system are shown in Table 4. The DG can generate voltage sag (0.1–0.9 pu, 10 ms–1 s), voltage swell (1.1–1.15 pu, 10 ms–1 s), under voltage (0.8–0.9 pu, $>$ 1 s), over voltage (1.1–1.15 pu, $>$ 1 s), and outage (0–0.1 pu) at the desired time and magnitude. The proposed DG is examined with different types of faults, as given in the following sections.

5.1. Generating single-phase voltage sag

Figure 8 shows a single-phase 40% voltage sag during 7.5 cycle intervals for a pure resistive load. S_a, S_b, and S_c are closed during normal operation. S_a is opened and $\overline{S}_a$ is closed during voltage sag by adjusting the phase

A time relay for 150 ms. S_a is closed again and $\overline{S}_a$ is opened when the voltage sag ends. Each division is 100 V for the voltage waveforms and 1.25 A for the current waveforms.

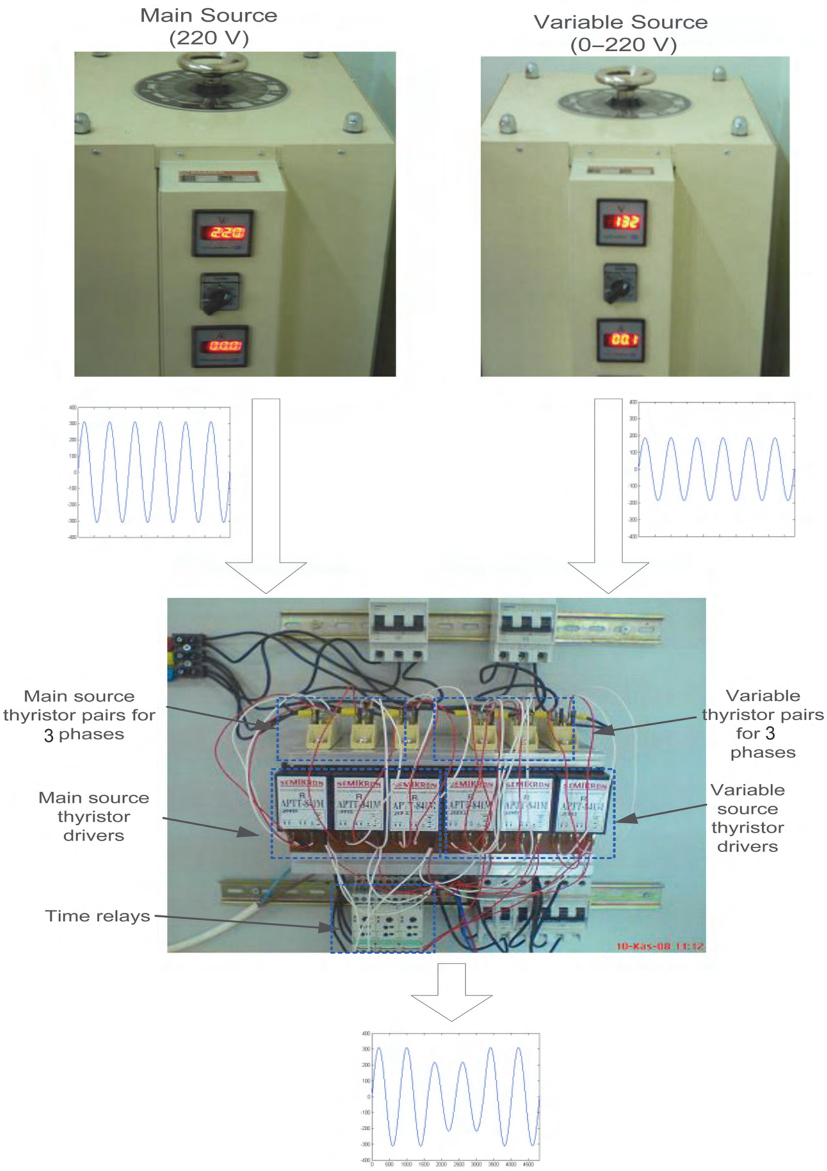

Figure 7. Experimental setup of the proposed DG.

Table 4. Specifications of the proposed system.

Primer voltage source	380 V, 50 Hz
Variable transformer	18 kVA, 50 Hz 380 V input, 0–435 V output
Power rating of the thyristors	1200 V, 40 A
Pure resistive load	148 Ω per phase
Inductive-resistive load	148+j95 Ω

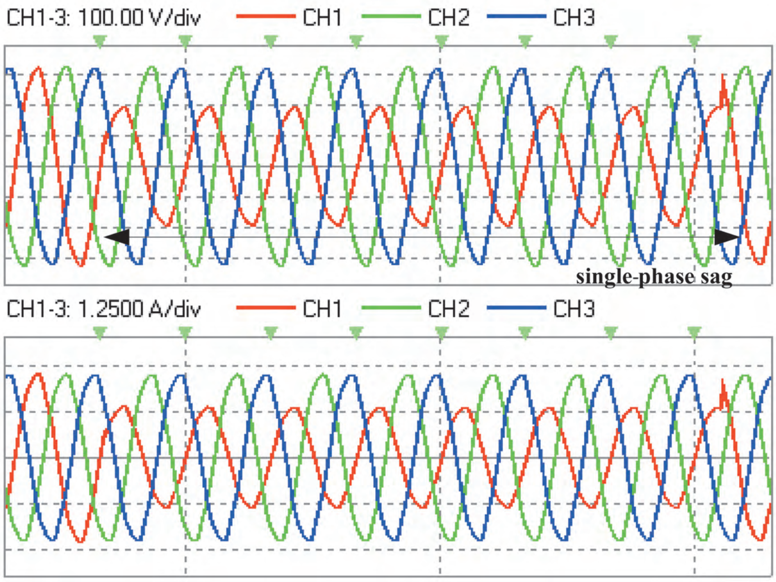

Figure 8. Single-phase voltage sag: a) voltage waveform and b) resistive load current waveform.

Figure 9 shows the transitions of the voltage and current waveforms when the voltage sag initiates.

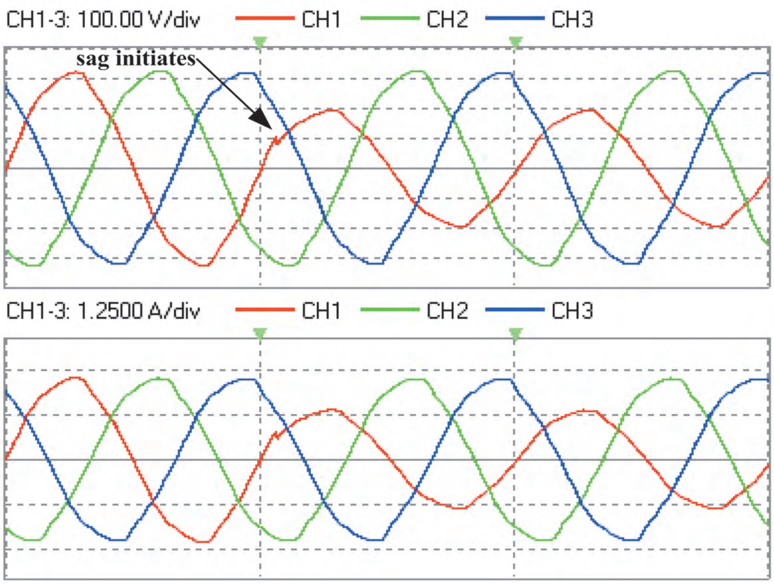

Figure 9. Starting of the single-phase voltage sag: a) voltage waveform and b) resistive load current waveform.

Figure 10 shows the transitions of the voltage and current waveforms when the voltage sag ends. As shown in Figures 9 and 10, the waveforms have no interruptions or transients during the transitions of the voltage sag.

5.2. Generating a double-phase voltage swell

A double-phase balanced 15% voltage swell occurs for 15 cycle intervals. S_b and S_c are opened and $\overline{S}_b$ and $\overline{S}_c$ are closed during a double-phase voltage swell by adjusting the phase B and phase C time relays for 300 ms.

Figure 11 shows the transitions of the voltage and current waveforms when the voltage swell initiates. Figure 12 shows the transitions of the voltage and current waveforms when the voltage sag ends. Each division is 100 V for the voltage waveforms and 1.25 A for the current waveforms.

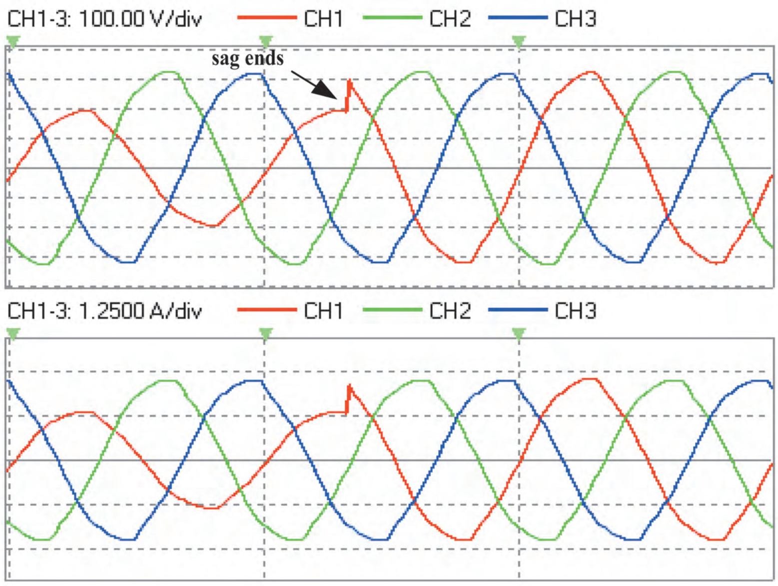

Figure 10. Ending of the single-phase voltage sag: a) voltage waveform and b) resistive load current waveform.

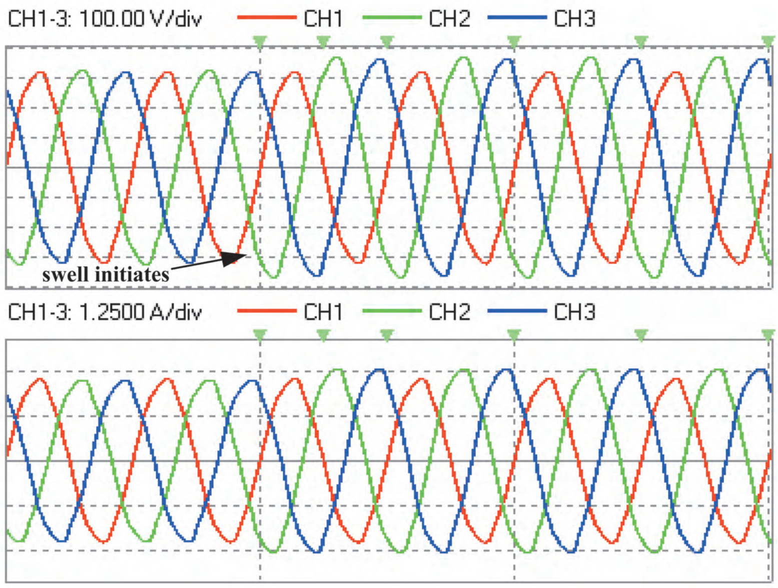

Figure 11. Starting of the double-phase voltage swell: a) voltage waveform and b) resistive load current waveform.

Transients are relatively small at the start and end of the voltage swell.

5.3. Generating 3-phase voltage sag

A 3-phase balanced voltage sag is generated by adjusting all of the time relays for 400 ms. S_a, S_b, and S_c are closed during nonfault conditions. Figure 13 shows the transitions of the voltage and current waveforms when a 3-phase balanced 30% voltage sag initiates. The voltage sag continues 20 cycle intervals for a 3-phase inductive-resistive load with a 0.85 power factor. S_a, S_b, and S_c are opened and $\overline{S}_a$, $\overline{S}_b$, and $\overline{S}_c$ are closed during the voltage sag. Each division is 100 V for the voltage waveforms and 1.25 A for the current waveforms.

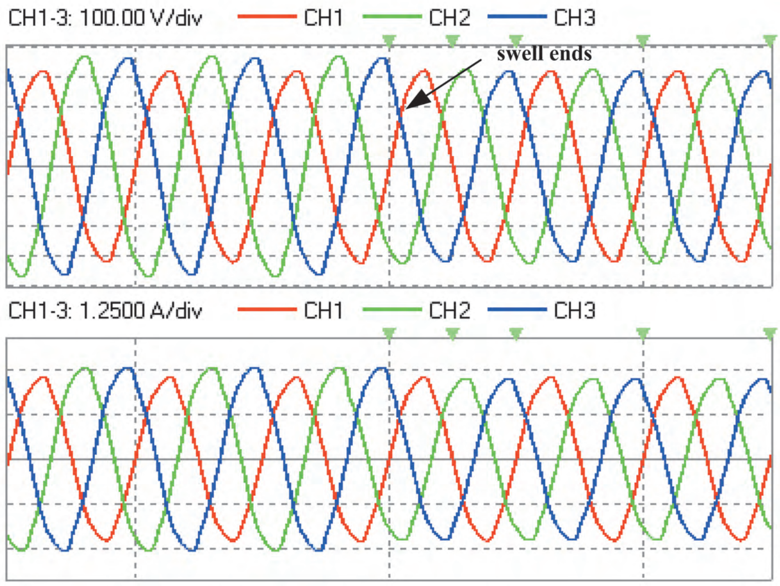

Figure 12. Ending of the double-phase voltage swell: a) voltage waveform and b) resistive load current waveform.

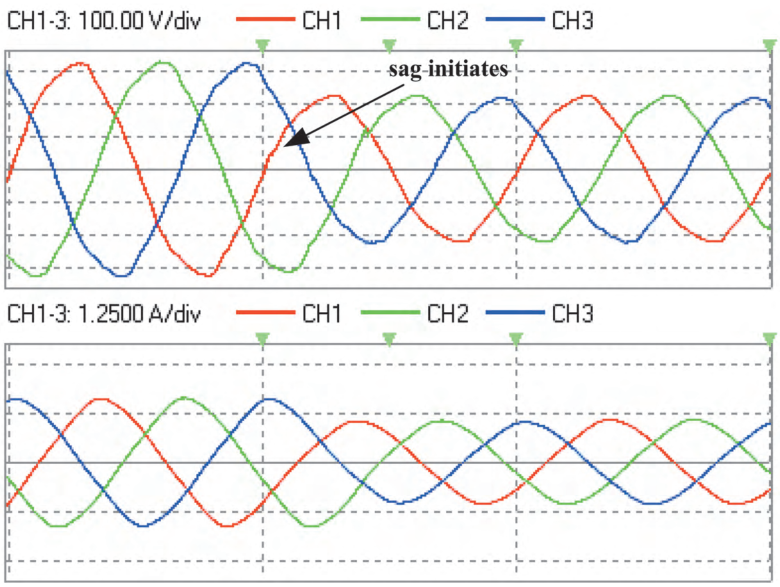

Figure 13. Starting of the 3-phase voltage sag: a) voltage waveform and b) inductive load current waveform.

Figure 14 shows the transitions of the voltage and current waveforms when a 3-phase balanced 30% voltage sag ends.

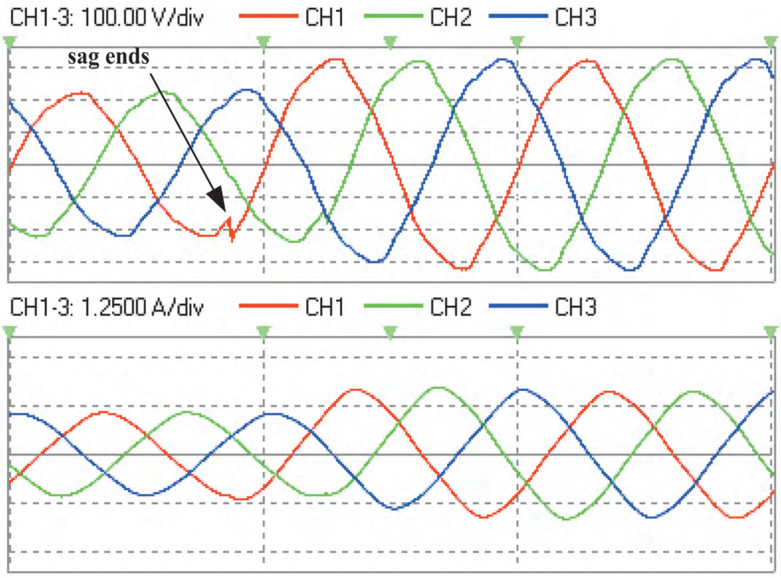

Figure 14. Ending of the 3-phase voltage sag: a) voltage waveform and b) inductive load current waveform.

It is observed that the transitions are clearly satisfied for the inductive-resistive load.

5.4. Testing a SSTS

The main components of the experimental system consist of the proposed DG, a SSTS, sources, and sensitive loads, as shown in Figure 15. In this system, the proposed DG is used for testing the SSTS [18].

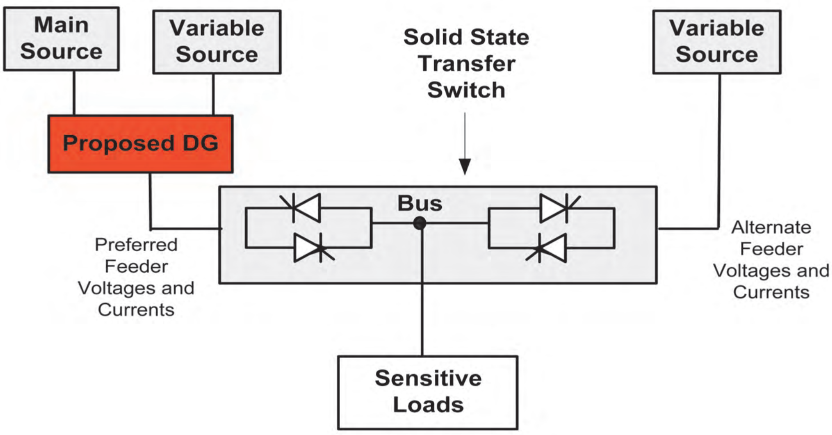

Figure 15. The main components of the experimental system consist of the proposed DG and a SSTS.

The basic structure of the SSTS system includes:

- A load that is sensitive to variations of the utility supply voltage.
- Two independent sources, of which the first is the preferred source and the other is the alternate.
- Two thyristor blocks that connect the load to the power sources.

- A control logic to monitor the phase-to-phase voltages of both sources, detect voltage sag and interruption, compare the 2 sources, and perform a load transfer from the preferred source to the alternate source if needed.

Figure 16 shows the performance of the SSTS in the case of 40% sags (decreasing from 380 V_{rms} to 235 V_{rms}) on 3 line-to-line voltages of the preferred feeder.

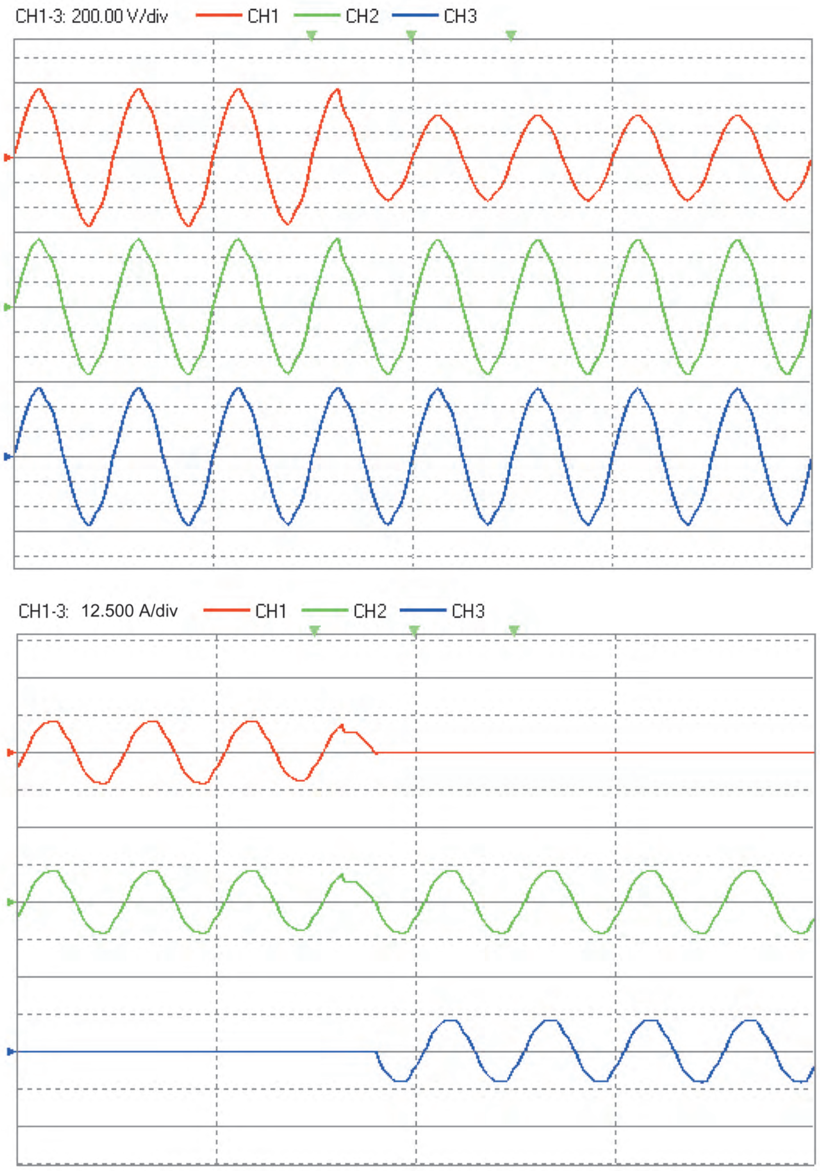

Figure 16. Voltage/current waveforms for 3 phases of the ground fault in the preferred feeder.

In Figure 16, the voltage waveforms of Ch1, Ch2, and Ch3 indicate the preferred feeder AB, bus AB, and alternate feeder AB voltages, respectively. Similarly, the current waveforms of Ch1, Ch2, and Ch3 indicate the preferred feeder phase A, bus phase A, and alternate feeder phase A currents, respectively. The proposed DG has generated a voltage sag successfully and the SSTS has been tested.

6. Conclusions

Nowadays, the interest in using high tech power electronic devices is increasing. These devices should be tested using DGs for identifying the responses to PQ disturbances. In this paper, the latest technological DGs and the proposed DG were comprehensively discussed and compared with focus on their usefulness, economic aspects, and simplicity. An experimental study illustrating the setup, design, and operation of the proposed 3-phase DG was presented. The graphical results for testing a SSTS were also shown. The proposed DG scheme has the advantages of being practical and cost-effective. The proposed DG is an optimum solution to generate sag, swell, unbalance, overvoltage, undervoltage and outage for testing PQMDs such as the SSTS, SVC, and UPS. The fact that the proposed system cannot generate harmonics and flickers is a known disadvantage.

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