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(54) Title: A POWER SIGNALING BASED TECHNIQUE FOR DETECTING ISLANDING CONDITIONS IN ELECTRIC POWER DISTRIBUTION SYSTEMS

# A POWER SIGNALING BASED TECHNIQUE FOR DETECTING ISLANDING CONDITIONS IN ELECTRIC POWER DISTRIBUTION SYSTEMS

## I. BACKGROUND OF THE INVENTION

Distributed generation (DG) has recently gained a lot of momentum in the power industry due to market deregulation. Figure 1 shows a power system with DGs connected. During normal operation, the distribution system and the DGs provide the power for the loads. The total power from DGs is typically small in comparison with the total feeder loads so the distribution system often provides the missing power. If the feeder becomes isolated from the distribution system due to, for example, the opening of breaker A, the feeder becomes a small unregulated power system. The behavior of this system is unpredictable due to the power mismatch between the load and generation and the lack of controllers. This operating condition of DGs is called islanding. In other words, islanding occurs when a portion of the distribution system becomes electrically isolated from the remainder of the power system, yet continues to be energized by distributed generators. An important requirement for distributed generation is the capability of the generators to detect island conditions and trip the generators accordingly. Failure to trip islanded generators can lead to a number of problems to the generator and the connected loads. The current industry practice is to disconnect all distributed generators immediately after the occurrence of islands. Typically, a distributed generator should be disconnected within 300ms to 1 second after loss of main supply according to prevalent DG interconnection standards.

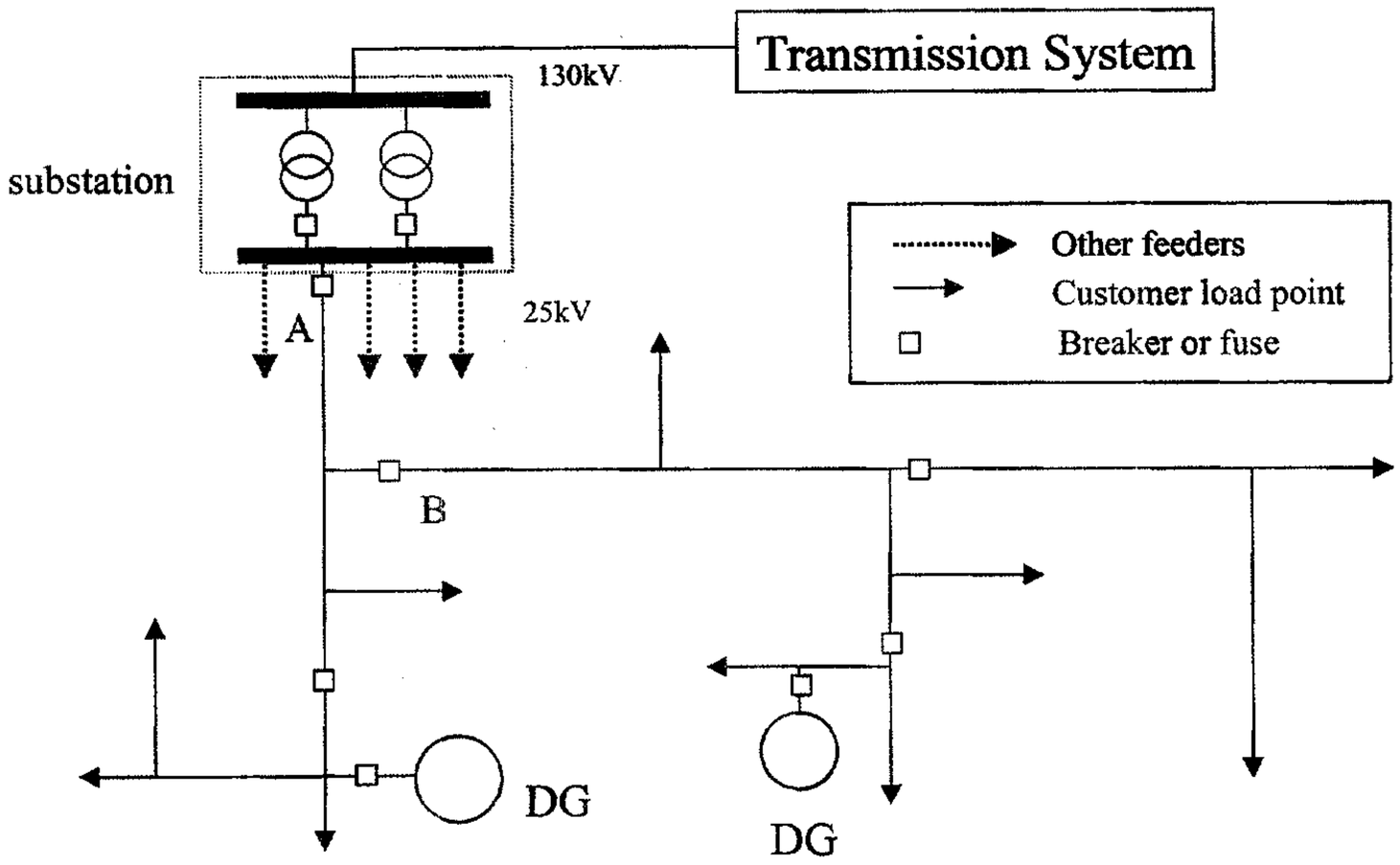



Figure 1: Typical distribution system with distributed generators.

To achieve such a goal, each distributed generator must be equipped with an islanding detection device. The common devices used for this purpose are the modified versions of the under/over voltage and under/over frequency relays. Representative examples of such relays are the Rate of Change of Frequency Relay (ROCOF) and the Vector Surge Relay (VSR), which is also known as vector shift or voltage jump relay. It is known if the generation and load have a large mismatch in a power system, the frequency of the system will change. In view of the fact that the frequency is constant when the feeder is connected to the distribution system, it is possible to detect the islanding condition by checking the amount and rate of frequency change. The ROCOF and VSR relays are based on such principles. This is the simplest islanding detection technique. However, it cannot function properly or fast enough if the generation and load mismatch is small. They often result in nuisance trips of DGs as well.

In order to overcome the above problem, a few active schemes that require a DG to inject small signals (or disturbances) to the system have been proposed. For example, the terminal voltage of the DG could be varied at a rate of 0.1Hz. Research has shown that such voltage variations could increase frequency change when the generator is islanded. So the frequency detection scheme can be improved by using this technique. This is an expensive scheme and there is a lack of field experience. One of the main challenges facing this scheme is the

interaction among the DGs that are introducing similar disturbances to the system. At present, there is no answer to this question yet.

In addition to the above local information based islanding detection schemes, techniques that use telecommunication means to trip islanded DGs have been used in industry. With this 'transfer-trip' scheme, each DG is equipped with a cellular phone like receiver. Breaker A has a transmitter that sends a trip signal to the DG receivers if it opens. With current telecomm technologies, there is no major technical problem to do so. The problem is the cost and complexity. Firstly, it is expensive for areas that are not covered by radio communications. Secondly each breaker needs a transmitter and there could be several of them between the DG and the substation. Thirdly, some of breakers need to be reconfigured and equipped with the capability of interfacing with the signal transmitter. Fourthly, feeder segments including their DGs could be reconnected to a different system due to the practice of feeder reconfiguration. In this case, A DG signal receiver must have the capability to decide which signal transmitters it should listen to.

In summary, as more and more distributed generators are added to utility systems, it is highly desirable to have a reliable and low cost islanding detection technique.

## II. SUMMARY OF THE INVENTION

This invention provides a new type of the islanding detection method that utilizes power line as a signal carrier. The proposed scheme is shown in Figure 2.

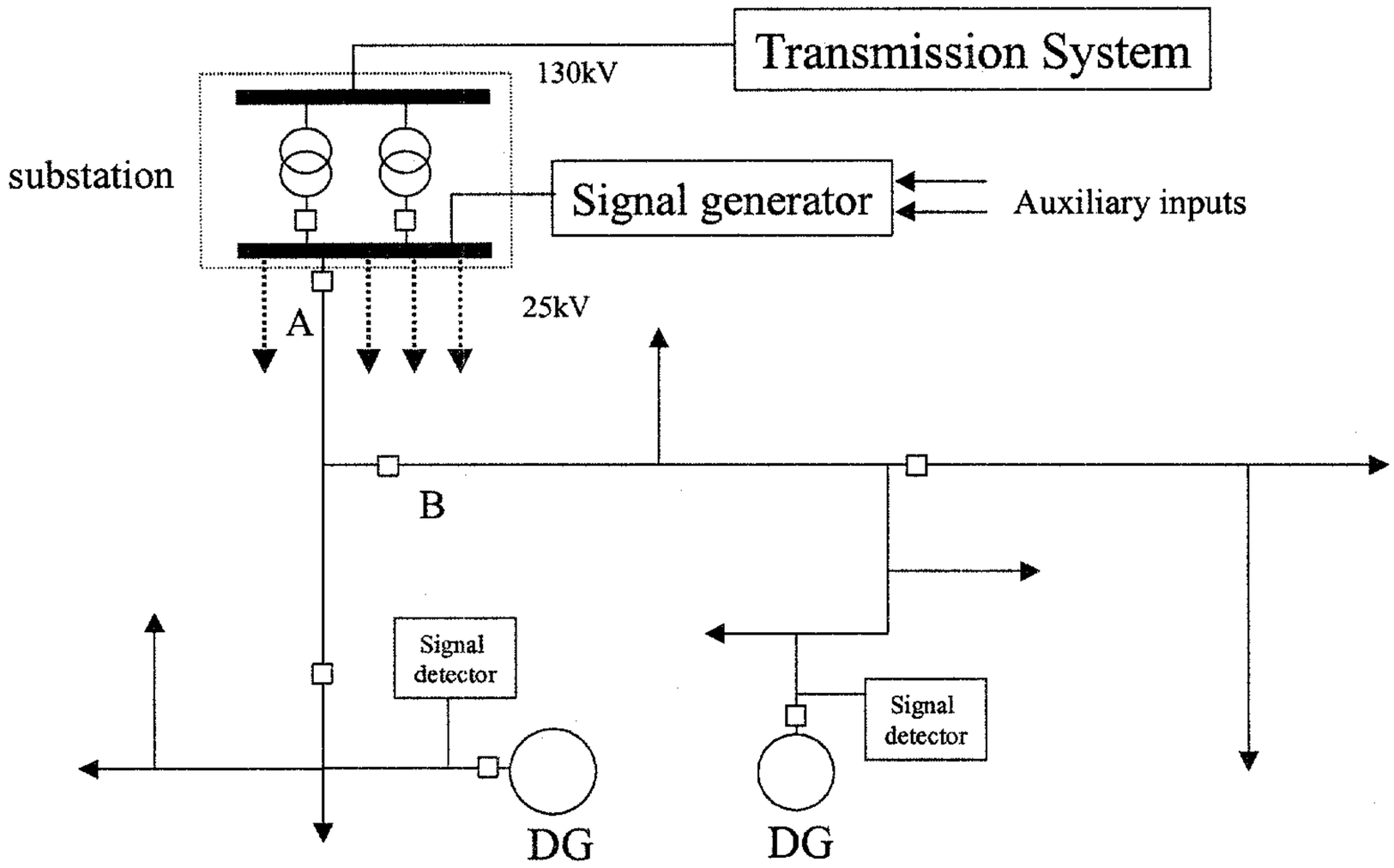



Figure 2: Proposed islanding detection scheme.

The invention includes two devices: a signal generator associated with a substation and a signal detector associated with a DG. The signal generator broadcasts a signal to all distribution feeders with a preset protocol continuously. If the signal detector associated with the DG does not sense the signal (caused by the opening of any breakers between the substation and the DG) for certain duration such as 200ms, it is considered as an island condition and the DG can be tripped immediately. If the substation bus loses power, which is another islanding condition, the signal generator also loses power and stops broadcasting so that downstream DGs will also trip. Furthermore, the signal generator has several auxiliary inputs. Any one of the inputs can stop the broadcast, resulting in tripping all DGs in the system. This feature is particularly useful when transmission system operators need to trip the DGs. It is also useful if a transmission system island is formed. Since the transmission system is well equipped with telecommunication means, it can send a stop signal to the signal generator.

A significant feature of this invention is that the signal generator can also be located in any places between the substation and the distributed generators. The signal generator is equipped with the capability to detect the opening of any upstream breakers. Once such a condition is detected, the signal generator will stop broadcasting and the downstream DGs will trip. In an extreme case, the signal generator can be placed at a particular DG site to equip that

DG with anti-islanding capability. We refer to this feature as the scalability of the technology. With the scalability, the technology can be used to protect all DGs served by a substation, by a feeder, or by a portion of a feeder. It can also protect individual DGs.

This invention is fundamentally different from the published schemes. It combines the positive features of the telecomm-based and the local detection based schemes. Power line is used as a telecomm medium. Another important advantage is that the scheme can be tested without actually breaking up the distribution feeders. The main tests could be done by simply stopping the signal generator. The signal detectors should detect zero signals in this case. When applied to individual DGs, the invention is also significantly better than existing methods and can be applied to any types of DGs. These benefits will become clear in the following sections.

## III. DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

There are many methods and apparatuses available or possible as communications systems for transmitting signals through power lines and for receiving such signals. Preferably the signal generator and the signal detector of the present invention provide a fast response, are reliable and scalable, and cause minimum or no interference with power line communication schemes that may already exist on a distribution system.

In a preferred embodiment, the present invention is implemented by injecting voltage signals to specific cycles of the voltage at the signal generator (SG) connection node. An example of the voltage waveform that contains the signal is shown in Figure 3. In this waveform, every second cycle contains a small distortion that is an indication of the existence of a signal. Depending on the requirement of response time and cost of signal generation, one can also let every third cycle or every fourth cycle contain the distortion.

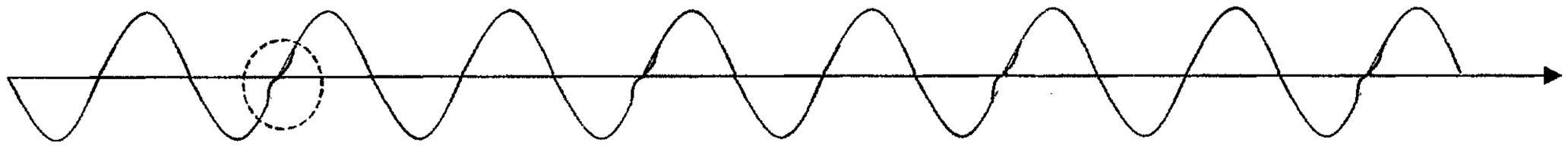


Figure 3: Sample voltage waveform that contains a voltage signal for islanding detection.
(signal pattern 010101010101)

In a preferred embodiment, the signal generator will also draw a pulse current from the upstream power distribution system at the same time of creating the voltage signal. A sample current waveform containing such pulses is shown in Figure 4. If the signal generator cannot draw an expected pulse current from the upstream system, it indicates that the device has been disconnected from the supply source and an island situation has occurred.

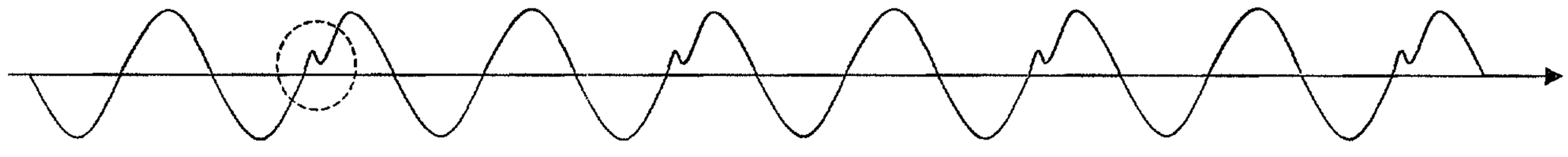


Figure 4: Sample current waveform that contains a current pulse for islanding detection.
(signal pattern 010101010101)

To avoid interference with similar signals used for automatic meter reading (AMR), the voltage and current signals can be injected at the instant that is far away from the distortion signals injected by the AMR device. The preferred embodiment is at the zero-crossing instant when the voltage is rising from a negative value to a positive value. In this case, it has been assumed that the AMR device sends signals around the zero-crossing instant when the voltage is going from a positive value to a negative value. This situation is shown in Figure 5.

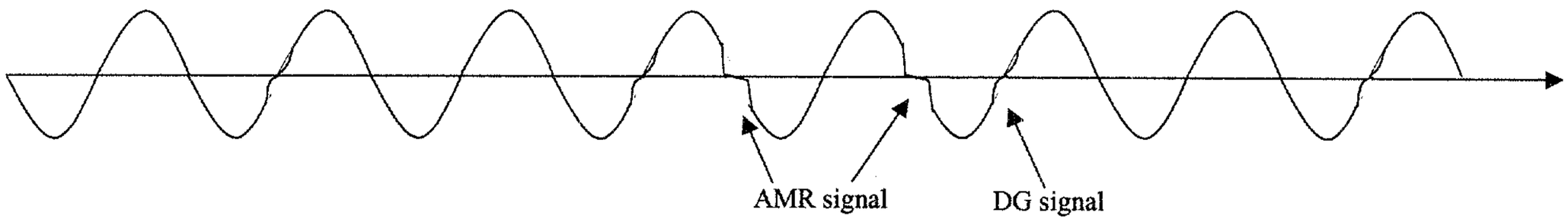



Figure 5: Sample waveform that contains signal for islanding detection and signal for other power line communication application.

The voltage signals can be injected on one or more of the three phase-to-ground voltages and one or more of the three phase-to-phase voltages, which results in a total of 6 signal channels. The pulse current can be also drawn from one or more of the three phase-to-ground paths and one or more of the three phase-to-phase current paths. To further avoid interference with the AMR device, the signals are preferably sent through a channel (for example, phase-A to ground) that is not used by the AMR device. A channel usage detection algorithm is preferably included to determine which channels are free for the signal generator to use.

In a preferred embodiment, the signal detector has two functions: 1) detect the presence of distortion at certain cycles of the voltage waveform and 2) determine if the distorted cycles follow a pre-established pattern such as one distorted cycle for every two cycles or for every three cycles.

The methods to generate and to detect the above described signals are presented next. The method to resolve the interference between the DG signal and AMR signal is also explained.

***A. Signal Generator***

The first component of the present invention is a signal generator. The signal generator may be comprised of any suitable method, system, device or apparatus which is capable of generating a signal in a power line and drawing a pulse current from the upstream system.

In a preferred embodiment, both the voltage and current signals are generated at the same time by short-circuiting the voltage selected to carry the signal, through a transformer impedance

and a thyristor. In the preferred embodiment, this process also draws a pulse current from the upstream system. Figure 6 shows the structure of the signal generator. In the preferred embodiment, the signal generator includes the following components/features as numbered in the figure:

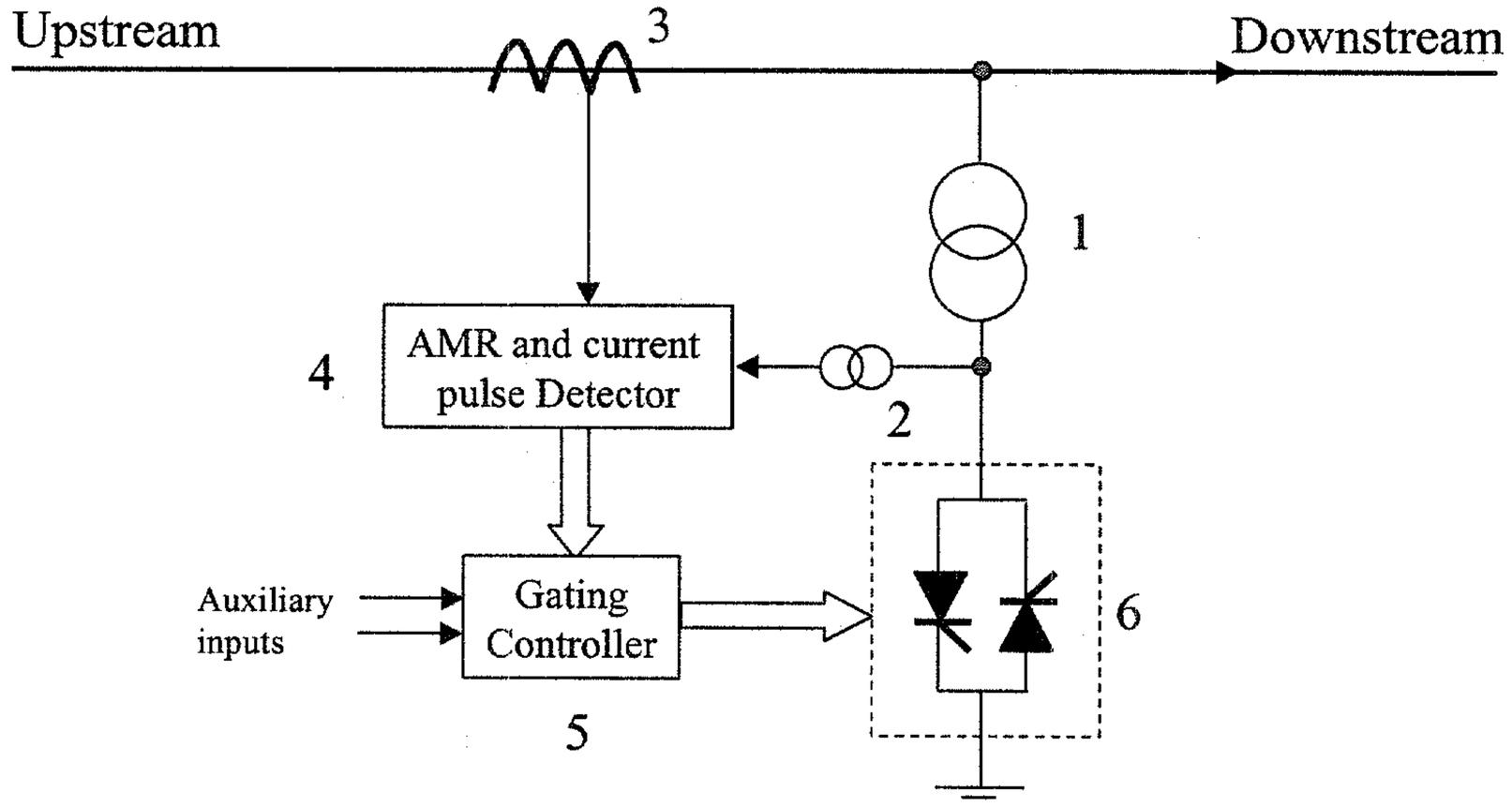



Figure 6: Architecture of the signal generator (one phase illustration).

1. **Step-down transformer:** In the preferred embodiment, a step-down transformer transforms the primary voltage (for example, 25kV or 14.4kV) to a reduced level (say 480V) for thyristor operation. The transformer also behaves as an impedance to limit the thyristor current and to reduce the amount of distortion introduced to the substation voltage. Common power transformer can be used. The impedance of the transformer may be selected according to the following equations:

$$X_T = \frac{U_N^2(\sqrt{2}\sin\delta - k_s)}{3S_{PG}k_s}$$

where

$X_T$ = Reactance of the signal transformer measured at the feeder primary side (Ohm)

$U_N$ = Supply system rated line to line voltage (V)

$S_{PG}$ = The supply system single phase to ground short circuit capacity (VA)

$\delta$ = Thyristor firing angle ahead of the zero crossing point (typically 30°)

$k_s = \frac{U_p}{U_{PG}}$ Relative strength of the signal to be detected. Typical value is 3% to 5%.

The peak of the current pulse drawn can be estimated from the following equation:

$$I_{peak} = \frac{\sqrt{2/3}U_N}{X_T + X_{sys}}(1 - \cos\delta)$$

where $X_{sys}$ is the system impedance. If the SG is disconnected from the system, $X_{sys}$= *infinity* and $I_{peak}$ approaches zero. $I_{peak}$ is independent of the load current flowing on the distribution line.

2. **Voltage transducer:** In the preferred embodiment, voltage transducers are used 1) to provide reference information to time the thyristor gating operation and 2) to determine the activity of the AMR devices. Common PT can be used for this invention.

3. **Current transducer:** In the preferred embodiment, current transducers are used to measure the pulse current drawn by the signal generator from the upstream system. It must be placed on the upstream side of the signal generator. Common CT can be used for this invention.

4. **AMR and current pulse detector:** If another similar power line communication device such as an AMR device is present in the distribution system, an AMR detector may be provided in order to determine activities of the AMR device. If the AMR detector finds that the AMR device starts to use one of the available channels (such as phase-A to ground voltage) for communication, the AMR detector may send a signal to the SCR gate controller to disable the use of that channel by the signal generator. As a result, the channel may be freed up for AMR use. Similarly, a previously unused channel may be activated for signal broadcasting. In the preferred embodiment of the present invention as described herein, it has been assumed that the AMR device will not use all channels simultaneously. In the preferred embodiment, the second function of the AMR device is to detect the pulse current drawn

from the upstream system. The presence of this pulse current indicates that the signal generator bus is still connected to the upstream system.

5. **SCR gating controller:** In the preferred embodiment, a controller may perform several functions. Firstly, it may establish the pattern of signal to broadcast, such as one distortion for every 2 or 3 cycles. Secondly, the controller may trigger the thyristor to conduct at $\alpha$ degrees before the zero-crossing of the voltage waveform when signal injection is needed for that cycle. Thirdly, it may decide which channel to disable/enable signal broadcasting based on the information provided by the AMR/Current detector. Fourthly, the controller is preferably equipped with auxiliary inputs and is preferably configured such that one of the inputs can disable the triggering operation. When this happens, the signal generator will stop broadcasting signals.

6. **SCR module:** In the preferred embodiment, the SCR module behaves as a switch to connect the transformer secondary to ground, leading to a momentary short circuit of the transformer secondary. The short circuit introduces a voltage dip to primary voltage. This voltage dip is the distortion needed to represent the presence of a signal. The current drawn by the SCR is a pulse current, which is generated from the upstream system. If such a current exists, it indicates that the SG is still connected to the supply system. The SCR module is preferably equipped with two anti-parallel units. Two anti-parallel units are needed to produce a signal in either polarity. The signal polarity is needed to distinguish the signal from the AMR signal or to avoid the production of excessive DC current (when the SG is not connected to the substation). For the later case, the signal is created with alternate polarities.

Typical waveforms associated with the SG operation are shown in Figure 7. The repetitive pattern of signals is shown in Figure 8.

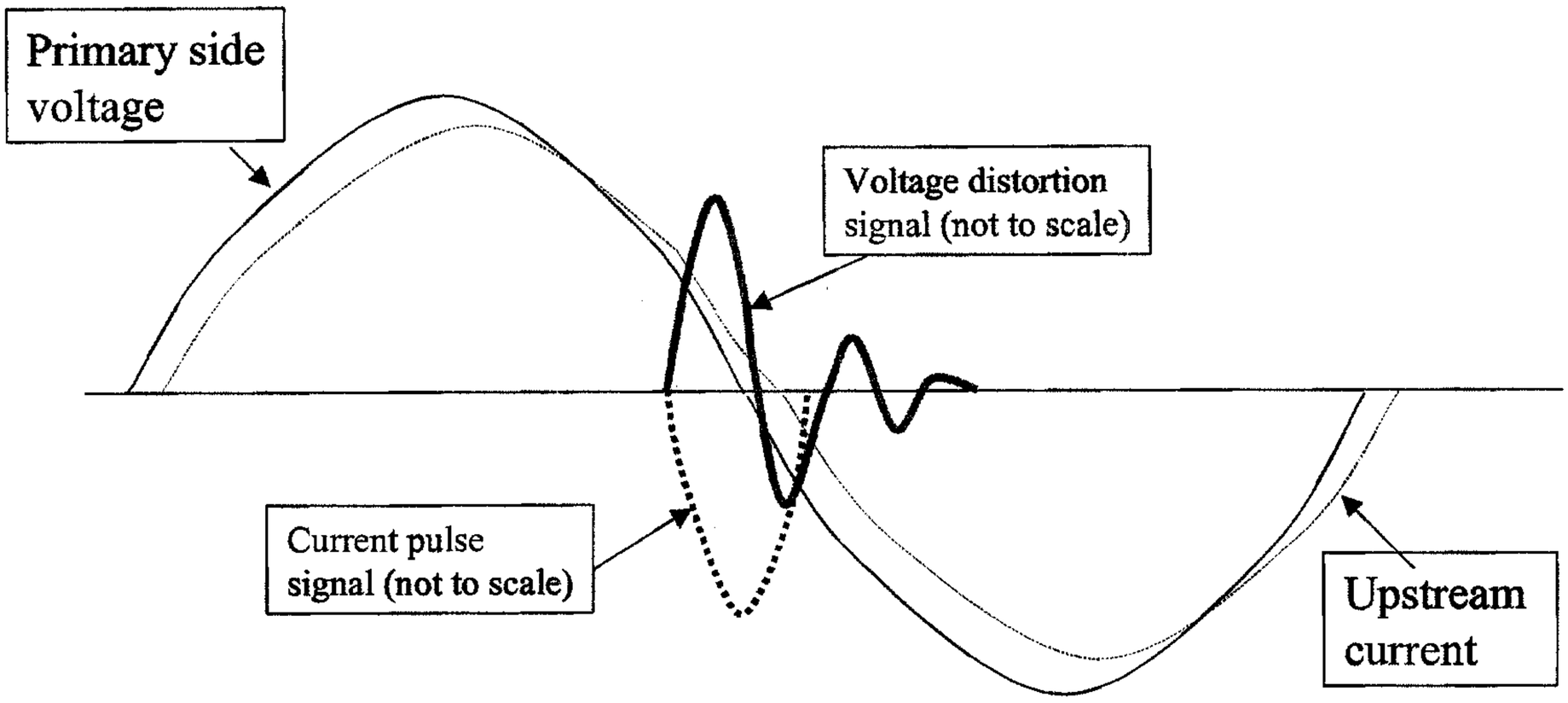



Figure 7: Typical voltage signal and current pulse produced by the SG.

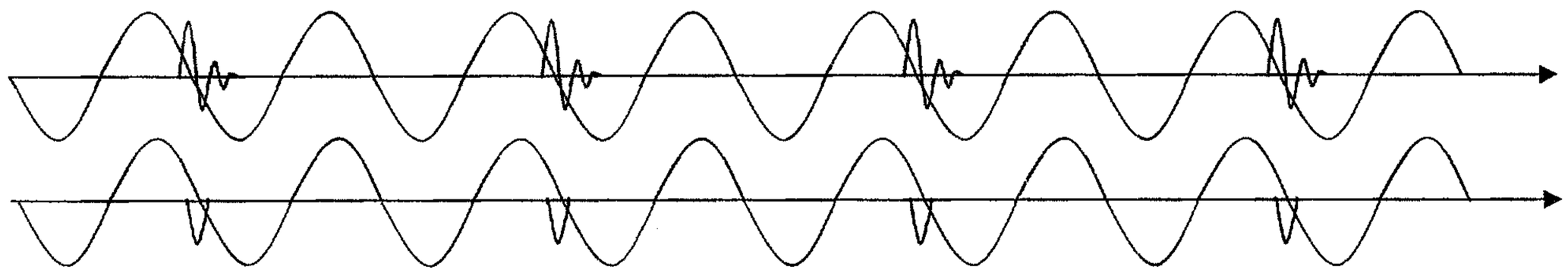


Figure 8: Signal pattern (up: voltage signal, down: current signal).

In the preferred embodiment of the present invention, there are three arrangements for the placement of the signal generators:

1) Connect the signal generator to the substation secondary bus: With this arrangement, the voltage signal will be broadcast to all feeders connected to the bus. There is no need to measure the current pulse since the check for connection to the 'upstream' is no longer necessary. The advantage of this arrangement is that one signal generator covers the needs of all DGs.

2) Connect the signal generator to any point of a distribution feeder: With this arrangement, the voltage signal will be broadcast to all nodes downstream of the connection point. The current pulse must be checked to determine if the SG is connected to the supply system. If the current pulse disappears, the SG should stop broadcasting. A typical application of this

arrangement is to connect the SG to the sending end of a feeder, just outside of the substation fence. The advantage of this arrangement is that one does not need to access to the substation and therefore cost can be reduced.

3) Connect the signal generator to the bus having a distributed generator: This arrangement uses the current pulse drawing capability of the SG to determine if the site is connected to the supply system. Broadcast of the voltage signal is not necessary if there is no DG in downstream. This is an opposite of the first arrangement. In this case, the SG transformer can be eliminated since the SG can be connected to DG terminal. The CT is preferably placed on the upstream side of the SG. The advantage of this arrangement is that one only needs to deal with one DG. The SG can be moved upward when more DGs are added.

***B. Signal Detector***

The second component of the present invention is the signal detector.

In the preferred embodiment of the present invention, the voltage signal detector is installed at the location in the distribution system where a distributed generator is connected. A current signal detector is preferably installed at the SG site and is expected to be a component of the SG equipment. Both the voltage and current signal detectors work in a similar way. The detectors sense the three phase voltages or currents at their respective locations. If either of the signals is not present, the signal pattern is not consistent with the pre-established rule, or the waveform frequency deviates significantly from power frequency (60Hz or 50Hz), and the signal detector will send a signal to trip the distributed generator or the signal generator. Accordingly, a signal detector preferably works like a relay and, in the preferred embodiment, the signal detector executes the function of voltage signal detection in a microprocessor-based relay. The voltage signal detection function therefore may become an added function to the microprocessor-based relays used in many distribution generator stations.

In the preferred embodiment the algorithm for signal detection is based on the principle of detecting the presence of the distortion signal. In the preferred embodiment, the distortion signal

is obtained by digitally subtracting two consecutive cycles of the measured waveform since the signal is present at most in one of the cycles. The difference between an undistorted cycle and a distorted cycle is the distortion signal. Due to changes and disturbances in power systems, the result of subtraction between two consecutive cycles, called the differential signal, can be different from the ideal signal waveforms. One of the main goals of the signal detector is to determine if the differential signal indeed represents a genuine distortion signal. There are a number of ways to accomplish this task. One of the algorithms proposed for signal detection is summarized below:

1) A signal template is stored in the detector. The template can be obtained by, for example, recording a 'good' signal during the normal operation of the power system;

2) The detector monitors the signal containing waveform on continuously;

3) The waveform is subtracted by the data of the previous cycle. The result is the differential signal;

4) The polarity of the subtracted waveform is detected to determine if it is a positive signal or a negative signal. A positive signal occurs if the cycle to be subtracted contains the signal. A negative signal occurs if the subtracting cycle contains the signal. An example signal pattern is shown in Figure 9.

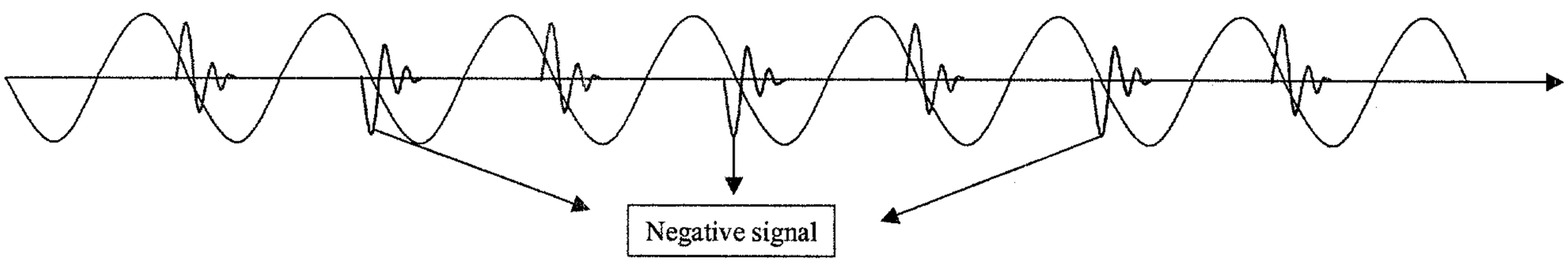



Figure 9: General pattern of the differential waveform (for every 2nd cycle signaling).

5) The 'distance' between the template and the differential waveform is calculated as follows (see Figure 10). The calculation is performed, say, from +60° to -60° of the signal period.

$$D = \frac{\sum_{i=1,n} [x_{template}(i) \pm x(i)]^2}{\sum_{i=1,n} x_{template}(i)^2}$$

where + sign is for the positive signal and - sign for the negative signal.

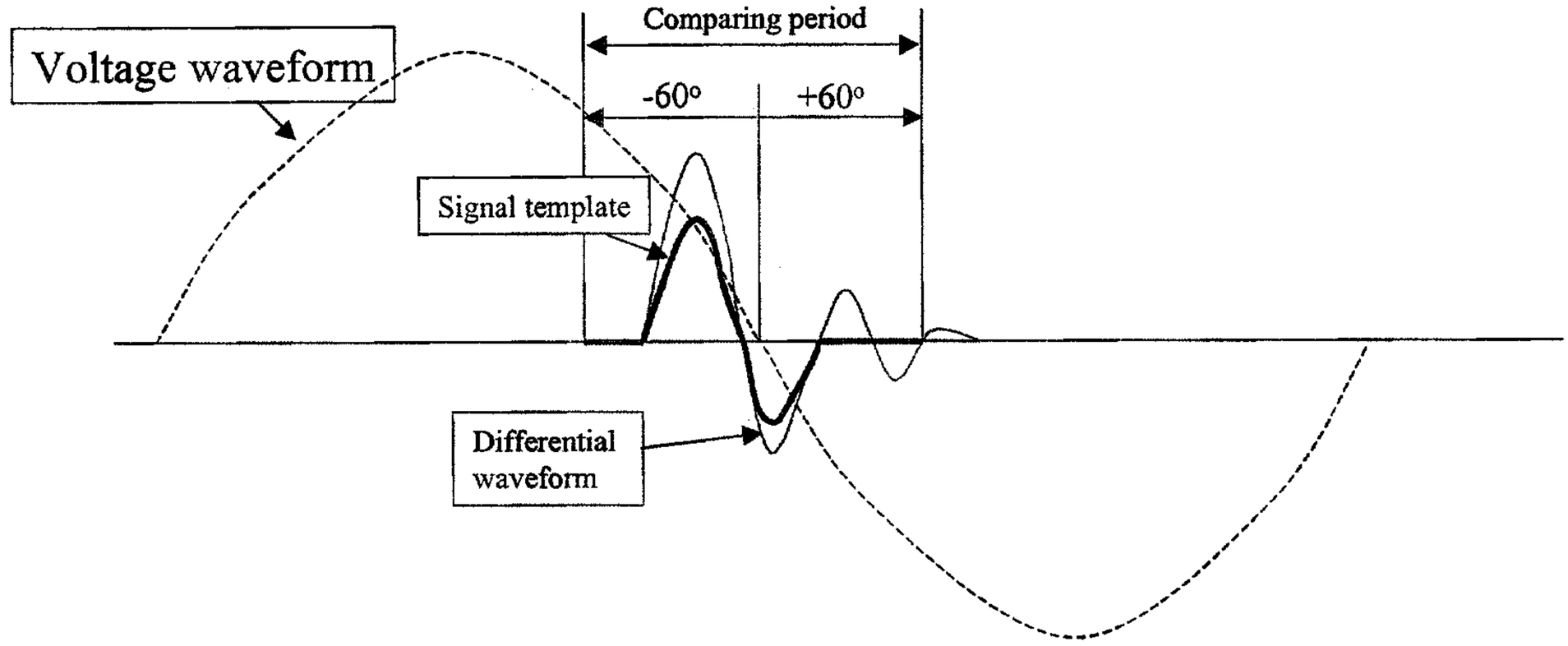



Figure 10: Signal detection method.

6) D is compared to a threshold. If D is greater than the threshold, a signal is considered as existent. Otherwise, the signal is considered non-existent.

7) If the signal does not exist continuously for a number of user specified cycles, the signal detector will send a trip signal to DG or SG.

## IV. Special Case - Application to Inverter-Based DGs

The inverter-based DGs contain power electronic components and have sophisticated controls. The components can be directly controlled to draw a pulse current from the supply system when the voltage is close to the zero-crossing point. The inverter controlled this way will have a built-in islanding detection capability. Preferably, a pair of anti-parallel thyristors can be added to the terminal of the inverter to achieve the same purpose. In this application, there is no need to distinguish upstream and downstream lines. The pulse current is drawn from the line

connecting the inverter. The advantages of this preferred pulse current drawing scheme, compared to other islanding detection schemes, include the following:

1) Since only the supply system can provide a large pulse current, the interference among multiple inverters using the preferred method is small. Furthermore, the pulse currents are synchronized among the inverters through the supply voltage. It further reduces the opportunity for interactions among the signal generators, or at least, it will help one to assess the degree of interference more easily.

2) If a large number of inverters are present and the disturbance of a system is a concern, a signal generator can be installed in the upstream, eliminating the need for a pulse current drawn by individual inverters. This scalable feature will reduce the power quality impact of the scheme when running on multiple inverters.

3) It is likely that the future inverter-based DGs will have two operating modes, grid-connected and intentional islanded operations. In a preferred embodiment, the proposed scheme is capable of detecting the grid change and facilitating the transfer from one mode to another, which is more advantageous than the positive feedback schemes. Such schemes will destabilize the inverters so intentional islanded operation is not possible. Due to the same consideration, the proposed scheme can be applied for inverters involved in micro-grid operations.

In summary, the present invention provides a reliable, easy to use and economical method, system and apparatus for detecting an interruption in an electrical power distribution system. The invention is particularly suited for detecting islanding conditions in electrical power distribution systems.

In one aspect, the invention may comprise the steps of transmitting at least one signal through at least a portion of a power distribution system, detecting an interruption in the receipt of the signal, and causing an action to be taken as a result of detecting the interruption in the receipt of the signal. Preferably the signal is transmitted in the form of a voltage signal over a period of

time, either as a continuous signal or signals or as a repeating signal or signals, so that interruptions in the receipt of the signal can be detected over the period of time. The signal may be comprised of a continuous single signal, a repeating single signal, or may be comprised of a plurality of identical or different signals which are associated with each other in a predetermined pattern or relationship and which are either transmitted continuously or repeatedly.

In another aspect, the invention may comprise the steps of drawing a pulse current from the upstream systems, detecting an interruption in the receipt of the pulse current signal, and causing an action to be taken as a result of detecting the interruption in the receipt of the pulse current signal. Preferably the signal is transmitted over a period of time, either as a continuous signal or signals or as a repeating signal or signals, so that interruptions in the receipt of the signal can be detected over the period of time. The signal may be comprised of a continuous single signal, a repeating single signal, or may be comprised of a plurality of identical or different signals which are associated with each other in a predetermined pattern or relationship and which are either transmitted continuously or repeatedly.

Preferably the signal or signals are transmitted by a signal generator, which may be comprised of any method, system, device or apparatus which is capable of drawing a pulse current from the upstream power distribution system and transmitting a voltage signal or signals through the power distribution system.

Preferably the detection of the interruption of receipt of the signal or signals is performed by a signal detector, which signal detector may be comprised of any method, system, device or apparatus which is capable of detecting the interruption of the receipt of the signal or signals and which is compatible with the signal or signals being generated.

The detection of the interruption of receipt of the signal or signals may reflect an interruption in the transmission of the signal or signals or may reflect an interruption in the receipt of the signal or signals.

Preferably the power distribution system includes a distributed generation (DG) system and preferably the detection of the interruption of receipt of the signal or signals is associated with the distributed generation system.

More preferably the detection of the interruption of receipt of the signal or signals provides an indication of islanding conditions in a distributed generation (DG) system associated with the power distribution system. Preferably the action which is caused to be taken as a result of the detection of an interruption in the receipt of the signal or signals is to "trip" the DG system.

The signal or signals may be comprised of a distortion of the electrical power waveform or may be comprised of a separate signal which is independent of or superimposed upon the electrical power waveform. A signal comprised of a distortion of the electrical power waveform may be comprised of an alteration of the shape, frequency or amplitude of the waveform. The signal may be continuous, may be applied to every cycle of the electrical power waveform, or may be applied only to selected cycles of the electrical power waveform.

In a preferred embodiment, the signal or signals are comprised of a distortion signal which distorts the shape of a selected portion of the electrical power waveform when the distortion signal is superimposed upon the electrical power waveform. In the preferred embodiment, the distortion signal is applied to selected portions of selected cycles of the electrical power waveform. The signal detection method utilizes the difference between two consecutive cycles of voltage or current waveforms to detect the presence of a signal.

Where the signal or signals is not continuous, the signal or signals are preferably transmitted on a repeating basis with a frequency which is high enough to provide a suitable "response time" for causing the action to be taken when an interruption in the receipt of the signal or signals is detected.

Where the invention is utilized to detect islanding conditions in distributed generation (DG) systems, the frequency of transmission of the repeating signal or signals should be such

that the system will facilitate "tripping" of the DG system within about 100 to about 600 milliseconds from the time of an occurrence of the islanding conditions. In the preferred embodiment, where the electrical power waveform has a frequency of about 60 hertz, the distortion signal is preferably applied to every second, third or fourth cycle of the electrical power waveform.

Where the invention is utilized to detect islanding conditions in inverter-based distributed generation (DG) schemes, a pair of anti-parallel thyristors is preferably added to the terminal of the inverter.