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Signal Scalability Paper

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A Scalable Power-Line-Signaling-Based Scheme for Islanding Detection of Distributed Generators

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***Abstract* — Power-line-signaling-based schemes are regarded as promising solutions to the problem of anti-islanding protection of distributed generators (DGs). These schemes broadcast dedicated signals from the distribution substation to the downstream DGs and, therefore, transform the detection of islanded DGs into the determination of the signal presence at the DG sites. This paper presents an improvement to a published power-line-signaling method. With this improvement, the signaling device can be located anywhere between the substation and the DG sites, creating the opportunity for designing customized anti-islanding arrangements for various DG interconnection scenarios. Simulations and laboratory tests show that the improved scheme can work reliably.**

***Index Terms*—Distributed generation, DG interconnection, islanding detection, power line signaling.**

I. Introduction

Islanding detection is a significant technical barrier in the fast-growing distributed generation industry. Islanding occurs when part of the distribution network becomes isolated from the main supply, yet continues to be energized by the distributed generators (DGs). According to current industry practices, the islanded DGs must be detected and disconnected within 100 to 300ms after the loss of the main supply [1][2].

Recently, many researchers have tried to develop reliable and economical schemes for islanding detection in different types of distributed generators [3][4]. One promising development has been the introduction of power-line-signaling -based anti-islanding schemes [5][6][7]. These schemes have the following advantages over the other existing ones. First, the new methods broadcast dedicated signals over power lines and transform the detection of DG islanding into the detection of signal reachability at DG sites. Theoretically, these methods can work regardless of the power imbalance situation in an island and the type of DGs involved [8]. Second, one signaling device satisfies the needs of all the downstream DGs and its cost can be shared among the DG owners. No interference caused by signal injections will occur. Third, these methods use power distribution lines as the signal carrier and require no extra telecommunication coverage. Therefore, these methods are much more economically practical than the transfer trip scheme [9]. Moreover, unlike this scheme, these methods work independently of network reconfigurations since the switching of any openable devices can be detected automatically. Field tests have been carried out to verify the new schemes and the results have been very promising.

This paper presents a further investigation of the scheme introduced in [5][6]. An important improvement is proposed to increase the original scheme's flexibility and adaptability. With this improvement, the signal-generation device can be located at any place between the substation and the DG sites. As the device moves downstream, the signal coverage area shrinks while the flexibility of implementation increases. For different DG interconnection scenarios, the signaling device can be located to meet the minimum requirement for the signal-coverage area. In this way, even if only a few DGs are interconnected in the distribution network, the power-line-signaling-based islanding detection can still be economically practical. In the improved scheme, the signaling device needs to monitor its connection status to the main supply by examining an extra current signal.

This paper is organized as follows. Section II introduces the idea of the improvement. Section III investigates how to detect the connection status of the signaling device to the main supply and develops a criterion. Section IV presents laboratory tests of the improved scheme. Section V discusses the design requirements for the signal generator, and section VI presents the conclusions.

II. The Concept of Signal Scalability

The original power-line-signaling-based scheme continuously broadcasts a voltage distortion signal (i.e., an anti-islanding signal) downstream from the substation and, therefore, transforms the detection of islanded DGs into the checking of signal continuity at DG sites [5]. As shown in the sample distribution system in Fig. 1, one signal generator (SG) installed at the substation secondary bus (Site-1) satisfies the needs of all the downstream DGs (DG1, DG2, and DG3…). The costs of the SG can be shared among the DG owners. However, depending on the ownerships of the substation and feeders, there are some practical issues to overcome. Because of deregulation, different companies may own the substation and its feeders. It can be difficult for a distribution company to install a device in the transmission substation. So the flexibility in locating the SG is an important feature. If there is only a

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limited number of DGs near the end of a feeder, it would be advantageous to install the SG just upstream of these DGs as the SG transformer's size could be reduced. The size of this transformer is closely related to the fault level at its location. When the SG is installed at the substation, a large signal transformer is often needed.

Our proposed solution is to move the SG downstream when only a few DGs are interconnected in the distribution network. As shown in Fig. 1, when only DG1 and DG2 exist, the SG can be moved from Site-1 to Site-2. In this way, the anti-islanding signal broadcast downstream by the SG has a smaller coverage area, which still contains DG-1 and DG-2. This arrangement avoids the need to access the substation, and a smaller signal transformer can be used. This feature of moving the SG downstream and having a variable coverage area and cost is called the scalability of the power-line-signaling-based scheme and makes the anti-islanding scheme more adaptable to various DG interconnection scenarios.

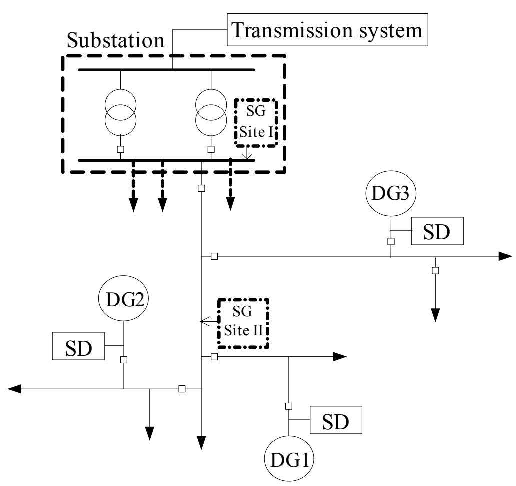

Fig. 1. A sample distribution system adopting the power-line-signalling based islanding detection scheme.

As the SG is moved away from the substation secondary bus, a new problem arises: how can we know if the SG is still electrically connected to the main supply? This condition must be monitored at all times. Once the SG is determined to be isolated from the main supply, it must stop broadcasting immediately and therefore trip all the downstream DGs.

We propose to detect the SG connection status to the main supply by monitoring the transient current signal flowing in the line at the upstream side of the signal generator. This current signal is created as a byproduct of the voltage distortion signal generation process. Fig. 2 shows the architecture of the signal generator in the improved scheme. The same stepdown transformer and thyristors as those in the original scheme are used to create the voltage distortion signals [5]. Moreover, a current transducer (CT) is installed at the SG upstream side, monitoring the line current. When the thyristor is fired to create a voltage distortion signal, a transient current signal flows through the CT. If the SG is connected to the main supply, this transient current will have a pulse-like shape (see Fig. 3). If the SG is disconnected from the main supply, the shape of this current waveform will be different. The transient current waveform can therefore be used for monitoring the SG connection status to the main supply. The transient current signal detector in Fig. 3 extracts the transient current using the subtraction method introduced in [5], and then determines the SG connection status using the algorithm investigated later in Section III.

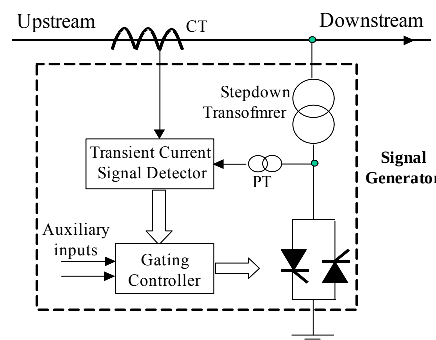

Fig. 2. The architecture of the new signal generator (one phase illustration).

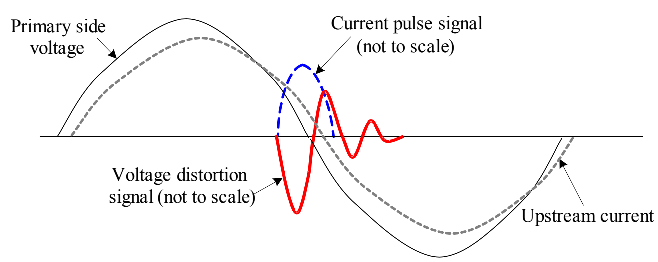

Fig. 3. Transient voltage and current signals created by SG when it is connected to the main supply.

The improved power-line-signaling-based scheme has been developed to suit various DG interconnection scenarios and to reduce costs. The signal generator can be installed at any place between the substation secondary bus and the DG sites. There are three possible arrangements.

1) The SG is installed just outside of the substation and connected to the sending end of a particular feeder. This arrangement is suitable for the scenario where many DGs are connected downstream and does not require access to the substation.
2) The SG is connected at any point along distribution feeders. A typical application of this arrangement is to connect the SG at the upstream of an area with many DG installations.
3) The SG is connected at the DG site. In this arrangement the SG can be directly installed at the DG terminal and does not require a stepdown transformer. Checking of the voltage distortion signal is not necessary. This arrangement is of low cost and is suitable for the scenario where only one DG exists.

With the above arrangements, the upstream current pulse must be checked to determine if the SG is connected to the supply system.

III. Detection of SG Connection to the Main Supply

The main challenge for the proposed scheme is to determine whether or not the SG is connected to the main supply according to the upstream transient current signals. When the SG is connected to the main supply (see Fig. 4(a)), the upstream transient current is a pulse-like signal. However, when the SG becomes isolated from the main supply, the shape of the transient signal changes. When the SG is at the feeder sending-end, this signal simply disappears when the SG becomes isolated. However, when a shunt capacitor is connected to the feeder before the SG (see Fig. 4(b)), the capacitor might mimic the main supply and contribute to a large transient current even when the SG is isolated from the main supply. The main objective of this paper is to identify the SG connection status in the second case. Computer simulations were performed to search for a criterion.

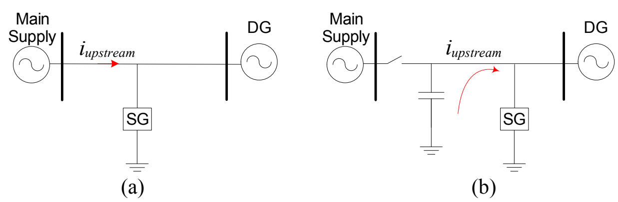

Fig. 4. Illustration of possible influence of shunt capacitors (a) SG at feeder sending-end and (b) shunt capacitor connected before SG.

A. Basic computer simulations

Fig. 5 presents a sample distribution system adopting the improved islanding detection scheme. Shunt capacitors are connected to the feeder before the SG. This system was simulated using PSCAD software and the parameters are listed below.

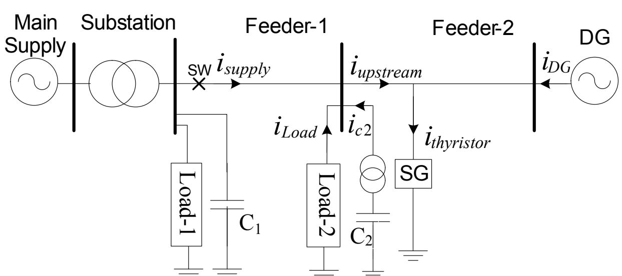

Fig. 5. The PSCAD simulation system.

- Transmission system: 3-phase, 230kV, 60Hz; three-phase-to-ground fault level is 5976 MVA; reactively grounded via a 1.5 ohm resistor.
- Substation: 230/25kV; 3-phase-to-ground fault level at the 25kV bus is 500 MVA.
- Feeders: segment 1 and 2 are both of 5km, and have parameters of R_1 =0.168 ohm/km, X_1 =0.379 ohm/km, R_0 =0.474 ohm/km, X_0 =1.164 ohm/km, $C_1 = C_0 =$ 0 μS/km.
- Load and shunt at the substation: Load-1 is 20MVA with a power factor of 0.95; each phase of Load-1 is modeled with a resistor in parallel with an inductor. Capacitor-1 is 5MVar. Both load-1 and Capacitor-1 are Yg connected.
- Load and shunt along the feeder: Load-2 is 2MVA with a power factor of 0.95; each phase is modeled with a resistor in parallel with an inductor. Capacitor-2 is 0.6Mvar. Both Load-2 and Capacitor-2 are Yg connected and fed via a 25/0.6kV, Yg/Yg connected transformer.
- DG: 5MVA, Z=25%; the DG transformer is 25/0.48kV, Yg/Δ connection, 6MVA, Z=5%.
- SG: the interface transformer is 25/0.48kV, 350kVA, Z=2.5%, Yg/Yg connected; the firing angle is 30°, a phase A to Ground (A-G) signalling channel is used. SG is installed at the sending-end of Feeder-2.

In simulations, an island was created by opening the switch SW at the sending end of Feeder-1. In the normal condition, this switch was closed. If for any reason this switch was opened, the SG became isolated from the main supply, and the DG was islanded. The SG was operated in both conditions, and the system responses to SG firing were simulated and are presented in Fig. 6 and 7, respectively.

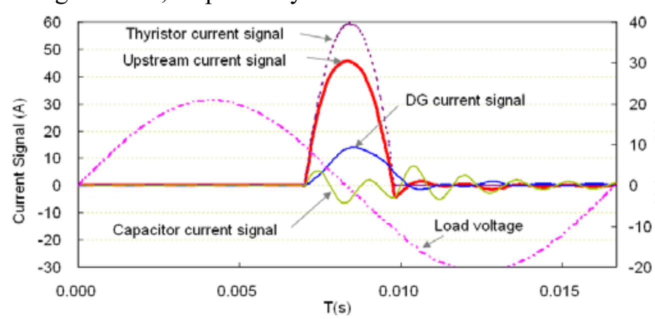

Fig. 6. The system responses to SG firing in normal condition.

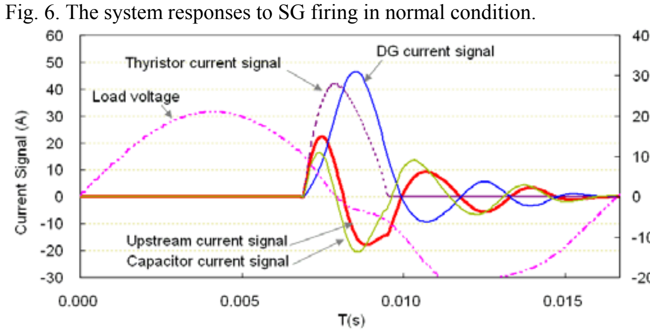

Fig. 7. The system responses to SG firing in SG isolated condition.

In the normal condition (Fig. 6), the SG upstream transient current signal is a positive pulse drawn mainly from the main supply and is close to the thyristor current waveform. However, in the SG isolated condition (Fig. 7), the DG supplies the majority of the thyristor current; the SG upstream current signal is composed mainly of the transient current flowing through capacitor-2 and is in oscillating form.

Discrete Fourier Transform (DFT) was performed to investigate the differences between the SG upstream current signals in the normal and SG isolated conditions. The input signals to DFT were of 2-cycle length, and were sampled at a rate of 256 points/cycle. The same settings are used for DFT later in this paper unless otherwise specified. The spectra of the upstream current signals are shown Fig. 8. In the normal condition, the upstream current signal contains abundant harmonic components (from the DC to the 7th harmonic) with a reduced energy level as the harmonic order increases. In the SG isolated condition, the energy of the upstream signal concentrates around the 5th harmonic. The most distinct difference between the normal and isolated condition signals is that the former contains much larger low-frequency components (from the DC to the 1.5th interharmonic).

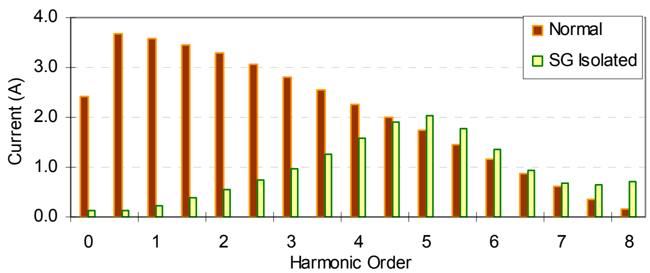

Fig. 8. Spectra of the upstream current signals.

B. Theoretical analysis and the detection criterion

This section verifies the findings in Section III by providing a through theoretical analysis and then develops a method for determining the SG connection status to the main supply.

Take the signal generator between phase A and the ground as an example. According to the superposition principle, the transient caused by thyristor firing can be analyzed with a network energized by a virtual voltage source $-v_{TA}$. The source $-v_{TA}$ is injected at the thyristor position to replace the thyristor during its conduction, and v_{TA} is the steady-state sinusoidal voltage across the thyristor when no signaling occurs. Denote

$$v_{TA}(t) = -\sqrt{2/3}U_N \sin \omega t \,, \tag{1}$$

where U_N is the rated phase-to-phase voltage, and ω is the fundamental angular speed.

Fig. 9(a) shows the analysis circuit for the simulation system in Fig. 5, where L_s and L_{DG} are, respectively, the self-inductance of the main supply plus feeder-1, and the self-inductance of the DG plus feeder-2; L_{SG} is the inductance of the SG stepdown transformer; R_L is the load-2 resistance; C is the shunt C2 capacitance. Load-1 and shunt C1 are ignored since they are in parallel with a very small main supply inductance, i.e., with almost an ideal voltage source. In the studied system, $(\omega L_s):(\omega L_{DG}):(\omega L_{SG}):R:(\omega C)^{-1}$ = 6:40:45:329:1042.

According to Thevenin's theorem, the circuit in Fig. 9(a) is equivalent to the circuit in Fig. 9(b) energized by a current source i_s in parallel with an inductor L_{SG}. If the thyristor is fired at instant $t_1 = -\delta/\omega$, the current source will be

$$i_s(t) = \sqrt{2/3}\,\frac{U_N}{\omega L_{SG}}\left[\cos\omega t - \cos\delta\right],\ (i_s \geq 0)\,. \tag{2}$$

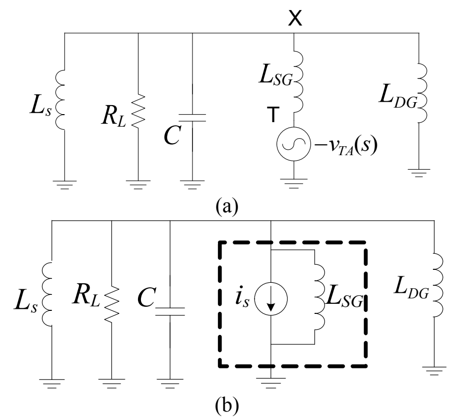

Fig. 9. Analysis of the upstream transient current signal.

Both the voltage and current sources are active only during the thyristor conduction period, which occurs from instant $-\delta/\omega$ to approximately δ/ω according to computer simulations. The waveforms of the virtual voltage and current sources are plotted in Fig. 10(a). The spectrum of such a current source is calculated using the DFT and is plotted in Fig. 10(b) for $\delta = 30^{o}$. This figure shows that this current source contains abundant harmonic components from the DC to the 7th harmonic, and that the energy level reduces as the harmonic order increases.

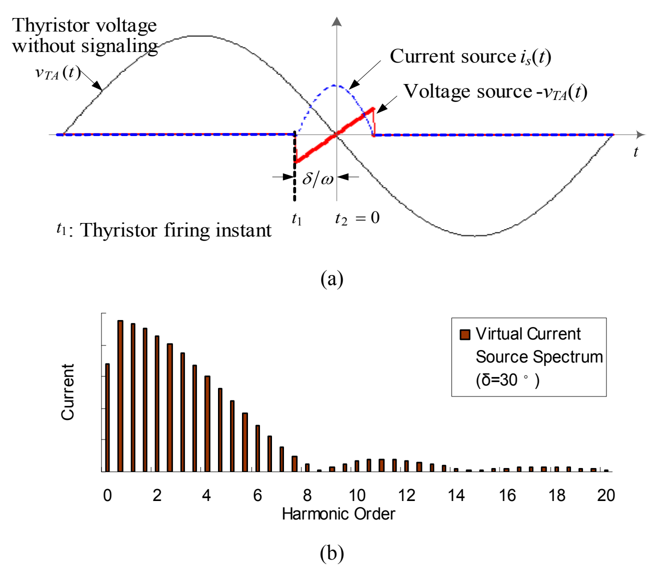

Fig. 10. The virtual voltage and current source (a) waveforms and (b) spectrum.

Frequency domain analysis was performed to explain how the harmonic components of the virtual current source flow in the network. The inductance L_s, inductance L_{DG}, load resistance R_L and capacitance C compose a parallel current-dividing circuit. The different frequency responses of the inductive, resistive and capacitive components determine the distribution of harmonic currents among them. The findings are as follows:

- Resonance occurs in the system at frequency

$$\sigma = 1/\sqrt{L_{eq}C}\,, \tag{3}$$

where L_{eq} is the system equivalent inductance, and L_{eq} equals $L_s // L_{DG} // L_{SG}$ in the normal condition and $L_{DG} // L_{SG}$ in the SG isolated condition.

- In the normal condition, $L_{eq} \approx L_s$. The simulated system is resonant at a very high frequency of the 15th harmonic. Therefore, the major components of the current source (the DC to the 7th harmonics) are divided mainly among the low-pass filters of L_s, L_{DG} and L_{SG}. The portion of the current flowing through L_s constitutes the upstream current signal.
- When the SG is isolated from the main supply, $L_s = +\infty$, $L_{eq} \approx L_{DG}$. The system is resonant at a lower frequency of the 5th harmonic. Large currents around the 5th harmonic flow through L_{DG} and C. The very low frequency component in the current source, such as the DC component, flows through L_{DG} and L_{SG}. Since the upstream current flows through C and R_L, it contains components around the 5th harmonic, and no DC component.

Frequency domain analysis of the circuit in Fig. 9(b) was also performed using computer and MATLAB software. The obtained upstream current signal spectra are shown in Fig. 11 and are very close to the results obtained through the time domain simulations shown in Fig. 8. This finding verifies the validity of the frequency analysis. The only difference in the results is that the resonance in the SG isolated condition occurs at the 5th instead of the 6th harmonic according to time domain simulations. This difference is due to the approximations made in the frequency domain analysis.

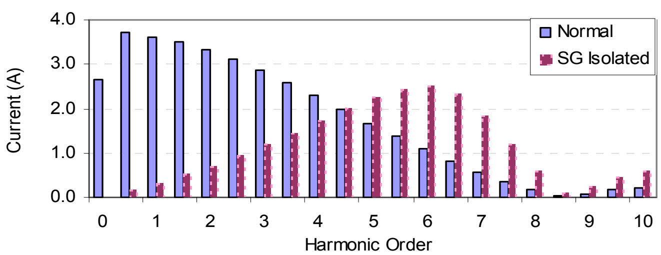

Fig. 11. Spectra of upstream current signals calculated with MATLAB.

Based on theoretical analysis, the low frequency (the DC to the 1st) harmonic components contained in the upstream current signal decrease sharply when the SG becomes isolated from the main supply. These components can therefore be used to construct a criterion for detecting the SG connection status to the main supply. In view of the workload, the DC component in the upstream current, I_{DC}, is chosen as the method used for detecting the connection status of the SG to the main supply. When I_{DC} is higher than a preset threshold, the SG is regarded as connected to the main supply. Otherwise, the SG is regarded as isolated from the main supply and should stop broadcasting immediately.

C. Sensitivity study

Sensitivity studies were performed using the sample distribution system and PSCAD software to test the validity of I_{DC} detection criterion. The following key system parameters were varied to determine their impacts on the DC criterion: the shunt capacitor C2 size, the 25kV substation fault level, the DG capacity, the load-2 capacity, the feeder length, and the distance from the SG site to the substation. The variations were shown as percentages of the base parameter values.

Fig. 12 plots the variation of the DC criteria with respect to the shunt capacity in both the normal and SG isolated conditions. Fig. 12 shows, the shunt capacity has a negligible impact on the DC criteria. A large vertical separation exists between the two curves corresponding to the normal and isolated conditions. This finding is of significant importance as the main purpose of this research was to find a reliable islanding detection method in the presence of large shunt capacitors.

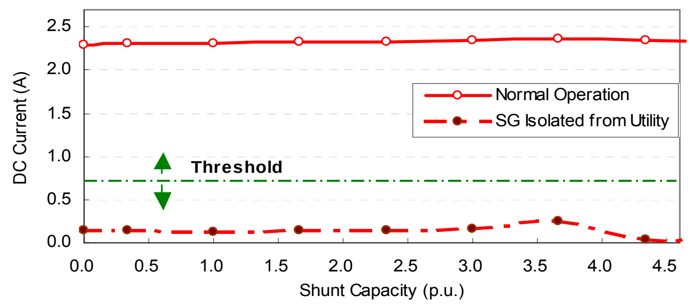

Fig. 12. Impact of shunt capacitor to the proposed DC detection criterion.

Fig. 13 shows the impact of the other system parameters. The substation fault level and DG capacity affect I_{DC} in opposite ways. In the normal condition, I_{DC} increases as the substation fault level rises and decreases as the DG capacity rises. In SG isolated condition, the I_{DC} is small and relatively constant. Therefore, with a low substation fault level or high DG capacity, the difference between I_{DC} values in the normal and SG isolated conditions would be small. However, the difference would still be large enough to support reliable detection according to the study of an extreme case where the substation and DG fault levels are equal (25MVA). Similarly, long distribution feeders or a large distance from the SG to the substation reduces the supply system fault level at the SG site and increases the detection difficulty, but cannot cause unreliable detections. A heavy load-2 slightly increases the I_{DC} in the SG isolated condition. However, even in the extreme case, in which the load is equal to the DG capacity, the SG isolated condition can still be clearly differentiated from the normal condition.

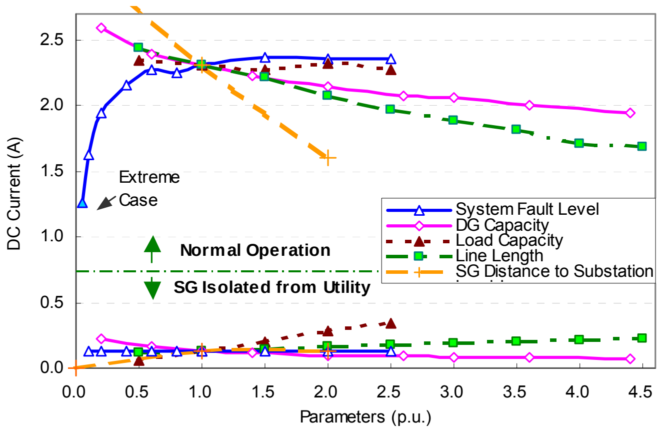

Fig. 13. Sensitivity study of the proposed DC detection method.

Fig. 12 and 13 show that a large difference exists in the upstream DC criteria in the normal and SG isolated conditions. For the studied system, a threshold can be set between 0.5A to 1A to reliably detect the SG isolated condition in various system configurations.

According to the simulations, in order to generate a voltage signal of 3% strength at the DG site, the required SG transformer size is 850kVA when the SG is at the substation secondary bus. This size reduces to 350kVA when the SG is moved to the site shown in Fig. 5. Therefore, moving the SG downstream can reduce the SG transformer related cost in the studied system.

IV. Experimental Tests

Laboratory experiments were performed in University of Alberta to confirm the effectiveness of the DC current criterion for islanding detection. The test system was constructed by scaling down the voltage level of a 25kV distribution system to 208V and reducing all its impedances by a ratio of 19.5. The original 25kV system has the same structure as the one in Fig. 5, except that Load-1 and C-1 do not exist. The system parameters are listed below.

- The distribution system: 25kV, 60Hz; three-phase fault level is 39.8MVA.
- The distribution feeder1 and feeder 2: both of 10km, R_{self} =0.2717 ohm/km, X_{self} =0.8886 ohm/km.
- DG: 5MVA, impedance of 25%; the DG transformer is 6MVA, with impedance of 5%.
- Load-2: 1MW, power factor of 0.9; each phase is modeled with a 625 ohm resistor in parallel with a 3.4H inductor.
- Capacitor-2: three-phase capacitor – size varies.
- Signal generator: transformer is 150kVA, 5% impedance, firing angle of 25°.

Fig. 14 plots the upstream current signals when the shunt capacity varies in a large range from 0 to 1.93 MVar. In the normal condition, the upstream current signal either is a positive pulse or contains a positive pulse. In the SG isolated condition, the signal is always oscillatory. According to the signal spectra in Fig. 15, in normal condition, the upstream signal contains relatively steady DC and 0.5th harmonic components. However, in SG isolated condition, the DC component in the upstream current signal is almost zero. Fig. 16 plots the DC current components as the shunt capacity varies, showing that the DC current criterion can be used to clearly distinguish the SG normal and isolated conditions with a threshold such as 0.015A.

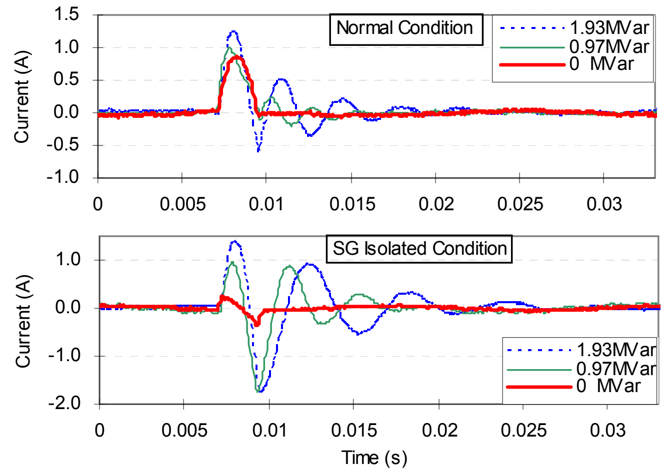

Fig. 14. The upstream current signals in normal and SG isolated conditions.

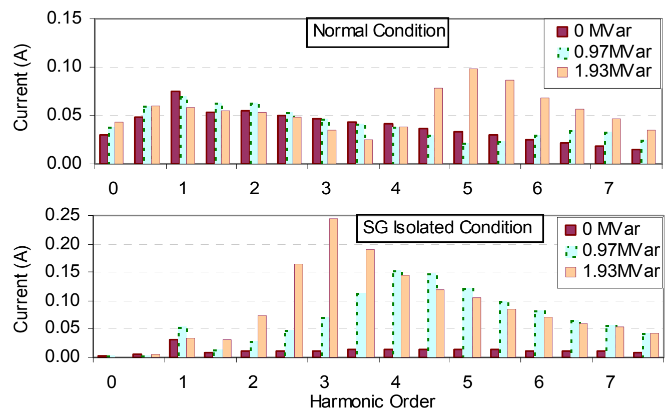

Fig. 15. The spectra of upstream current signals obtained in laboratory tests.

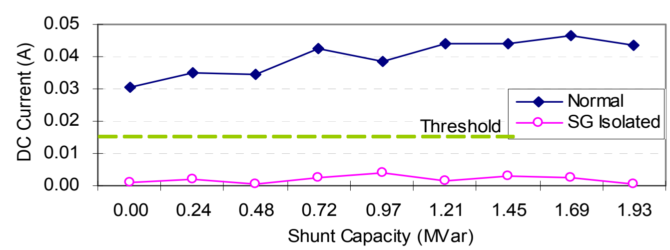

Fig. 16. The DC criteria in laboratory tests.

In Fig. 16, the normal-condition DC current criterion slightly rises from 0.03A to 0.045A as the shunt capacitance increases. This DC level is different from the relatively constant DC level in Fig. 12 because the SG firing angle in the tests was not ideally fixed. It actually slightly varied with respect to the shunt compensation level. Overall, the tests verified the effectiveness of the DC current detection criterion and demonstrated the feasibility of the improved islanding detection scheme.

V. DESIGN OF THE SIGNAL GENERATOR

In the improved power-line-signaling based scheme, the design of the signal generator needs to meet the requirements for both the voltage signal strength and the thyristor voltage and current ratings. The formulas for the signal transformer size and thyristor ratings in [5] still apply. Moreover, to facilitate the detection of its connection status, the signal generator must be able to draw a large enough DC current from the main supply in the normal condition. The analysis below shows that this requirement can be naturally met for signal generators installed at the distribution level.

According to [5], the DC current drawn from the main supply by the SG in the normal condition equals

$$\begin{aligned} I_{DC} &= \frac{2\sqrt{6}k_v S_{PG}}{\pi N U_N}\left(1-\frac{\delta}{\sin\delta}\cos\delta\right) \ \text{(SG : Phase − Ground)} \\ &= \frac{\sqrt{2}k_v S_{3ph}}{\pi N U_N}\left(1-\frac{\delta}{\sin\delta}\cos\delta\right) \ \text{(SG : Phase − Phase)} \end{aligned} \quad , \quad (4)$$

where k_v is the designed voltage signal strength defined with the voltage signal peak; S_{PG} and S_{3ph} are the supply system phase-ground fault level and three-phase fault level at the SG installation site, respectively; N is the interval between two firing events in the unit of the number of cycles. Therefore, for fixed voltage signal level k_v and firing angle δ , I_{DC} is proportional to the system fault level. Given the typical phase-ground fault level of 25kV systems from 20 to 150MVA, $k_v = 5\%$, $\delta = 30°$ and $N = 4$, the calculated I_{DC} ranges from 2.9 to 21.8A (SG between phase-ground).

To determine whether a DC current of 2.9 to 21.8A is discernible or not, we compare it with the normal load current flowing on the line. If the load capacity is proportional to the system fault level, the load current can be calculated using

$$\begin{aligned} I_{load} &= S_{PG} / (\lambda U_N / \sqrt{3}) \qquad \text{(SG : Phase − Ground)} \\ &= \sqrt{3} S_{3ph} / (\lambda U_N) \qquad \text{(SG : Phase − Phase)} \end{aligned} \quad . \quad (5)$$

In (5), λ is a constant of, say, 20, which means that the system fault level is 20 times of the load capacity. The ratio of the DC signal to the load current (RMS value) is calculated as follows:

$$\begin{aligned} k_I &= \frac{I_{DC}}{I_{load}} = \frac{2\sqrt{2}k_v\lambda}{\pi N}(1-\delta\frac{\cos\delta}{\sin\delta}) \quad \text{(SG : Phase − Ground)} \\ &= \frac{\sqrt{6}k_v\lambda}{\pi N}(1-\delta\frac{\cos\delta}{\sin\delta}) \quad \text{(SG : Phase − Phase)} \end{aligned} \quad .(6)$$

With the above assumptions, the current ratio k_I is determined by k_v, λ, N and δ and is independent of the system fault level. Given the above values, $k_I = 2.1\%$ (and 1.8%) for phase-ground (and phase-phase) signaling.

Our field measurement experiences with voltage distortion signals were referred to for evaluating the calculated DC current signal strength. In [5], voltage signals with average RMS strength of 0.85% could be reliably detected. Therefore, a DC current signal with a RMS strength of 2.1% (or 1.8%) has a good chance of being reliably detected. This result means that a signal generator installed at the distribution network can draw a large enough DC current for detection of its connection status to the main supply.

VI. CONCLUSION

This paper proposed an important improvement to a power-line-signaling-based islanding detection scheme by increasing its adaptability to different DG interconnection scenarios. With the improvement, the signal generator can be located at any place between the substation and the DG sites. The signal generator installation no longer requires access to the substation, and this feature is convenient for the distribution utility. In a typical arrangement, the signal generator can be connected at the upstream of an area with DG installations. In this way, the costs of the signal generator can be reduced and shared among the DG owners.

In the improved scheme, the signal generator must have the ability to detect its connection status to the main supply. The signal generator does so by examining its upstream transient current signal created during the signaling process. The level of the DC component contained in this transient signal is used as the criterion for determining the connection status. A high DC current means that the SG is connected to the main supply, while a low DC current means that the SG is isolated from the supply. The computer simulations and experimental tests all showed that this criterion can work reliably in various system conditions.

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