The detection of the occurrence of islanding is considered to be of paramount importance in order to integrate Distributed Generation (DG) to the electric grid system. The fact that most DGs, for example, photovoltaic (PV), fuel cell, and wind turbines are inverter-based, signifies the DC-Link voltage to be a potential candidate for passive islanding detection. The major problem of passive islanding detection is the occurrence of large non-detection zone (NDZ). The DC-Link voltage has a narrower NDZ in comparison with that of Under/Over Voltage (UOV). This paper provides further significant reduction in the NDZ of the DC-Link voltage using data detrending algorithm implemented in MATLAB/Simulink on a 100 kW PV grid-DG model. The selectivity of the method in non-islanding transient faulty conditions is also tested and is found to uniquely classify the grid-side faults distinctively.

Keywords: DC-Link voltage; distributed generation; islanding detection; non-detection zone; photovoltaic; under/over voltage.

1. Introduction

There is an unprecedented increase in the integration of distributed generation (DG) in the electric grid system to meet up with the increase in electric power demand, cushion the effects of rising costs and depletion of fossil fuels and also to reduce the harmful environmental impact [1]-[3]. Standard interconnection requirements for DG-grid integration such as IEEE 1547 and UL 1741 stipulates islanding detection as a significant prerequisite. Islanding is a situation whereby the local load and a DG remain connected in the absence of the utility source [4]. This is considered to be a dangerous situation for the local load, DG and utility maintenance personnel. Therefore, islanding should be detected, and the DG cut off within a maximum of two seconds [5].

Inverter-based islanding detection can be categorized into passive and active techniques. The passive technique is based on the Point of Common Coupling (PCC) parameter measurements for islanding detection whereas, the active technique deliberately injects and measures disturbance signal parameter at the inverter output. The most basic passive techniques are the under/over voltage (UOV) and under/over frequency (UOF). The most critical drawback associated with the passive techniques is their inherent large non-detection zone (NDZ) [2], [6]-[7]. NDZ is a situation in which the occurrence of islanding upon the failure of the electric grid goes undetected by the anti-islanding device when the power mismatch between the DG and its local load is negligibly small or zero. It is a parameter used to determine the effectiveness of an anti-islanding detection device. The smaller it is the better the technique used.
This paper proposes a method for improving the NDZ of DC-Link voltage used as an alternative parameter for islanding detection. The concept of using the DC-Link voltage as a passive islanding parameter was first introduced in [9].

2. Notation

The list below provides the used notation for this paper.

*Constants:*
- $P$ rated DG power [kW]
- $Q_f$ Quality factor (1.8)
- $P_L$ local load power [kW]
- $\Delta P$ grid power [kW]
- $\Delta P/P$ DG-load power mismatch [%]
- $K_I$ voltage controller integral gain
- $K_P$ voltage controller proportional gain
- $V_{DC}$ measured DC-Link voltage [V]
- $V_{DC1}$ pre-islanding measured DC-Link voltage [V]
- $V_{DC2}$ post-islanding measured DC-Link voltage [V]
- $V_{DCref}$ reference DC-Link voltage
- $\Delta V_{DC1}$ detrended DC-Link voltage [p.u.]
- $\Delta V_{DC2}$ Voltage controller output [p.u.]
- $V$ RMS value of phase voltage [V]
- $V_L$ RMS value of line-line voltage [V]
- $V_{max}$ utility allowable maximum voltage [V]
- $V_{min}$ utility allowable minimum voltage [V]

3. System model used for the study

In Figures 1 and 2, the block and circuit diagrams respectively, of the system used for the study, which is implemented in MATLAB/Simulink is shown. It is made up of principally three parts: a 0.1 MW photovoltaic DG with the associated control system; local load modelled as parallel RLC network; and the distribution part of the electric grid, modelled as an impedance behind the grid voltage. The three parts discussed are connected on a common ac bus, the Point of Common Coupling (PCC). The controller ensures a unity power factor operation of the DG such that only clean real power is injected into the grid. Details of the controller design and system parameters can be found in [10].

Fig. 1. Block diagram of the study model.
When the two circuit breakers in Figures 1, CB1 and CB2 are closed, the system is said to be in grid-connected mode. The system is said to be in islanded mode if CB1 is opened, separating the utility distribution network from the DG [11]-[12]. In the islanded mode, the load is supplied by only the DG. This brings about post islanding parameter variations at the PCC and the DC-Link voltage, in proportion with the power mismatch between the DG capacity and the load power.

Figure 2 shows a variant of inverter constant power control that uses the DC-Link voltage control as the external control loop. This loop forms the reference current value of the inner current control loop. The control function is achieved using the synchronous reference frames of the abc-to-dq0 transformation blocks. It is therefore assumed that the power injected into the grid is the same as that power generated at the inverter input from a PV or fuel cell source.

Fig. 2. Constant power inverter control [11].

Fig. 3. The electric power grid system
3.1 Non-detection zones of UOV

The NDZ of the UOV was the yardstick used for the evaluation of the NDZ associated with the DC-Link voltage parameter. Utility distribution allows a variation of 0.88 to 1.1 p.u. of the nominal supply voltage. Therefore, any difference that falls within this range is considered to be in the standard voltage operation window. As such, any power mismatch between the DG and the local load that causes the voltage to change within the window will remain undetectable by the UOV relay in the event of islanding. This situation is referred to as the NDZ of UOV evaluated by equation (1) [9]

\[
\left(\frac{V^2}{V_{\text{max}}} \right)^2 - 1 \leq \Delta P / P \leq \left(\frac{V^2}{V_{\text{min}}} \right)^2
\]  

(1)

Considering the system nominal voltage as 1 pu and substituting the allowable voltage variations, the NDZ is numerically expressed as (2):

\[-17.36\% \leq \Delta P / P \leq 29.13\%
\]  

(2)

3.2 Load model and power mismatch setting

The inverter load is modelled as a parallel RLC circuit. The parameter values are calculated from equations 3, 4 and 5.

\[
R = \frac{V_L^2}{P}
\]  

(3)

\[
L = \frac{V_L^2}{2\pi f * Q_f * P}
\]  

(4)

\[
C = \frac{Q_f * P}{2\pi f * V_L^2}
\]  

(5)

The inverter is controlled to operate at unity power factor. Therefore, it generates only real power while the reactive power is set to zero and the system resonates at the fundamental frequency. As such, the parameter that corresponds to the real or active power of the load is R as in equation 1. Therefore, power mismatch setting is done by setting the value of R in proportion to the mismatch value. The power mismatch setting is easily done using the Three-Phase Parallel RLC Load block of Matlab SimPowerSystems.

3.3 Non-detection zones of the DC-Link voltage

The flowchart in Figure 4 summarizes the methodology adopted by [9] for the determination of the NDZ of the DC-Link voltage and is itemised using the following steps:

1. Set the required power mismatch; starting with zero mismatches, when load power is equal to 100 kW and increment in steps of ± 5% up to 40%.
2. Measure the DC-Link voltage, \( V_{\text{DC}} \)
3. Switch off the circuit breaker, CB1 at time \( t = 3 \) seconds to represent the occurrence of islanding mode.
4. Compare the pre-islanding DC-Link voltage $V_{DC1}$ with that of the post-islanding voltage $V_{DC2}$

5. If the value of $V_{DC2}$ is not equal to $V_{DC1}$ return to step 1 for another power mismatch setting

6. If the value of $V_{DC2}$ is equal to that of $V_{DC1}$ the non-detection zone of the DC-Link voltage is attained

7. Stop the algorithm.

The result obtained by the method using the above algorithm is shown in Figure 4 with islanding occurring at time $t = 3s$. It could be observed from the result that for the DG-load power mismatches less than or equal to 20% there is no variation in the post islanding DC-Link voltage. However, at the mismatches greater than 20% the variation in the DC-Link voltage becomes evident as illustrated by the curves for 30% and 40% respectively in Figure 5. Thus, the NDZ for the DC-Link voltage was said to be 20% since all variations between the pre and post islanding values show no difference for mismatches less than or equal to 20%.

For the proposed NDZ improvement, power mismatch set point, $\Delta P/P$ is always chosen within the values bounded by equation (2).

3.4 Detrending algorithm for the NDZ improvements

According to [13], for a grid-connected VSI (Figure 2), the active power interchange information is accessible through the dc-link voltage regulator signal. It is also observed by [14] that in an electrical power system with randomly varying loads, estimation of electromechanical modes can be made using ambient data analysis starting with the application of detrending algorithm on the system’s raw frequency data for the removal of steady-state bias. Given the above, the DC-Link voltage is detrended to remove the steady state bias of the nominal dc voltage and to pass the result to a controller with the control law stated in equation (6).
\[ \Delta V_{DC2} = K_P \Delta V_{DC1} + K_I \int \Delta V_{DC1} dt \]  

(6)

The parameters of \( K_P \) and \( K_I \) are tuned such that the output of \( \Delta V_{DC2} \) is around unity \([8]\).

\[ \Delta V_{DC1} = V_{DC_{ref}} - V_{DC} \]  

(7)

4. Methodology

The simulation of system model in Figures 1 and 2 was made in MATLAB Simulink. The DG is said to be grid-connected if circuit breaker CB1 is closed. The occurrence of islanding is represented by the opening of CB1, disconnecting the grid from the PCC. In islanding mode, only the DG is powering the local load in the absence of the electric grid. Therefore, for grid-connected mode, the load power is given by

\[ P_L = P + \Delta P. \]  

(8)

The power mismatch setting is expressed as in equation (9) and represented in Table 1. Computations are made based on 100 kW DG capacity.

\[ \frac{\Delta P}{P} = \left( \frac{P_L - P}{P} \right) \times 100\% \]  

(9)

The methodology in this paper is same as illustrated in the flowchart of Figure 4, except that the measured DC-Link voltage is detrended and the resulting noise used as the input to the voltage controller as shown in Figure 6. Now the new variable for islanding detection at the controller output is \( \Delta V_{DC2} \). Data is generated for \( \Delta V_{DC2} \) at each of the mismatch settings to compare its performance with \( V_{DC} \) reported in Figure 5.

![Fig. 6. DC-Link voltage detrending.](image)

Figure 3 shows the details of the components comprised in the Grid block diagram as illustrated in Figure 1. A distant grid fault causing transients events is simulated using the three-phase Fault Breaker. In order to monitor the effects of grid-side transient faults on to the DC-Link voltage different fault types are initiated at time \( t = 1s \) that lasted for six cycles. The respective responses are therefore monitored.
Table 1: Power mismatch

<table>
<thead>
<tr>
<th>( P_L ) (kW)</th>
<th>( \Delta P / P ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>+25</td>
</tr>
<tr>
<td>115</td>
<td>+15</td>
</tr>
<tr>
<td>105</td>
<td>+5</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>95</td>
<td>-5</td>
</tr>
<tr>
<td>85</td>
<td>-15</td>
</tr>
<tr>
<td>75</td>
<td>-25</td>
</tr>
</tbody>
</table>

5. Results and discussion

5.1 Islanding Condition

Figure 7 shows the results obtained by using the detrending algorithm when islanding occurred at t = 3 s. It comprises the instances for cases where \( P_L \geq P \) and instances where \( P_L \leq P \). It can be seen from the results that there is a distinct variation in the detrended DC-Link voltage even at as low as \( \pm 5\% \) power mismatch against the results obtained in [9], Figure 5, which has significant variations only for a mismatch of \( > 20\% \). The combined responses of the detrended DC-Link voltage for all considered power mismatches can also be seen in Figure 7. It can also be observed that the post islanding detrended DC-Link voltage is always a straight line proportional to the power mismatch. This can be a good distinctive factor for faults and transient conditions.

![Fig. 7. \( \Delta V_{DC2} \) For all considered load power mismatch.](image)

5.2 Non-islanding transient fault conditions

On the other hand, the DC-Link voltage is monitored for peculiarities due to transients at different grid-side fault types. Figure 8 shows the single-phase to ground faults at various power mismatches. It has revealed a unique trend irrespective of the power mismatches. In
Figure 9 also, a unique trend is observed for the phase-phase-ground and two-phase faults. Three-phase faults are equally uniquely shown in Figure 10.
5. Conclusion

In this paper, a presentation of a method to improve the non-detection zone of a DC-Link voltage used as a passive parameter for the detection of the occurrence of non-intentional islanding was made. It can be concluded, from the results obtained, that the use of the detrending algorithm has increased the sensitivity of the islanding detection using inverter DC-Link voltage by significantly reducing the NDZ from $>20\%$ in the previous study to $\pm 5\%$ power mismatch. The results also presented the potentials of the method for discerning transients as the post islanding DC-Link detrended voltage is a constant power mismatch proportionate step. From the DC-Link voltage monitoring due to various transients at different power mismatches, it can also be concluded that different types of faults can be uniquely identified. Each fault type shows a peculiar wave pattern, despite the power mismatches between the DG capacity and the local load. Therefore, the sensitivity and selectivity of the method for both islanding and non-islanding events is shown.

References


