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Performance of the OVP/UVP and OFP/UFP Method With Voltage and Frequency Dependent Loads

H. H. Zeineldin, Member, IEEE, and James L. Kirtley, Jr., Fellow, IEEE

Abstract—In previous literature, constant RLC loads were assumed to impose, on the islanding detection method, the hardest detectable case. For this reason, distributed-generation (DG) islanding studies are usually analyzed and performed by using constant RLC loads. In this paper, different types of loads are taken into account by modeling the load’s voltage and frequency dependence. The performance of the over/undervoltage and over/underfrequency protection (OVP/UVP and OFP/UFP) method is examined for the different load models and the results are compared with the constant RLC load case. The analysis is conducted on a constant power-controlled DG designed to operate at unity power factor. A generalized formula, for calculating the nondetection zone of the OVP/UVP and OFP/UFP method, is derived in terms of the load’s voltage and frequency dependence parameters. The analysis is further extended on a constant current-controlled DG interface.

Index Terms—Distributed generation (DG), inverter, islanding, over/underfrequency, over/undervoltage, static load models.

I. INTRODUCTION

Islanding is a condition in which a part of the utility system, which contains load and generation, is isolated from the rest of the utility system and continues to operate. Un-intentional islanding commonly occurs on low voltage secondary distribution systems with interconnected DG. However, the IEEE standards do not allow islanding and necessitate its disconnection once an islanding condition occurs [1], [2]. The detection of an islanding condition can be achieved through either a passive, active or communication based islanding detection method. A comprehensive survey on the different islanding detection methods could be found in [3], [4]. Recently, a data mining approach was proposed to extract information that could be used in identifying an islanding condition. The proposed method utilizes various system parameters and then a decision tree approach is utilized to classify non-islanding from islanding cases [5].

One of the commonly used islanding detection methods is the over/undervoltage protection (OVP/UVP) and over/underfrequency protection (OFP/UFP) method, which is the main focus in this paper. Despite its simplicity and easiness to implement, the method suffers from a large nondetection zone (NDZ).

NDZ could be defined as the values of loading for which an islanding detection method would fail to detect islanding. The NDZ concept is commonly used for evaluating the performance of islanding detection methods. Islanding detection methods, developed for inverter-based DG, generally focus on the following:

1) DG with interface controls designed to supply constant power;
2) loads represented by constant RLC loads.

Recently, in [6] and [7], the impacts of the DG interface control design on islanding detection and NDZ were examined. The NDZ of the constant current-controlled DG interface was found to be smaller than the constant power-controlled DG interface. It was concluded that the choice of the DG interface control has an effect on the NDZ and on the choice of the suitable islanding detection method. In [8], the effect of voltage-dependent loads on the operation of an induction generator during an islanding condition was examined. The voltage and frequency deviation were found to be dependent on the load model [8].

Generally, islanding detection methods are tested and analyzed by using constant RLC loads. It has been assumed in the literature that constant RLC loads constitute the hardest detectable condition for an islanding detection method [7]. This paper investigates the accuracy of this assumption by taking into account different types of loads with various voltage and frequency dependence parameters. The impact of the load’s voltage and frequency dependence on islanding detection and NDZ is examined. The load’s voltage and frequency dependence parameters are varied independently to determine the sensitivity of the OVP/UVP and OFP/UFP method to variations in load parameters. A general mathematical formula is derived, in terms of the load parameters, for calculating the NDZ of the OVP/UVP and OFP/UFP method. The analysis is further extended on a constant current-controlled DG interface.

This paper is organized as follows. Section II provides a brief introduction on static load models. Section III presents the system and DG interface model under study. Section IV highlights, through simulation results, the performance of the OVP/UVP and OFP/UFP method for the different load parameters. Section V focuses on the impacts of the load parameters on NDZ. Finally, conclusions are drawn in Section VI.

II. STATIC LOAD MODELS

A load model that expresses the active and reactive power of the load as functions of voltage and frequency is a static load model. There are various ways of modeling the load’s voltage dependence, which could be through a polynomial or exponential relationship. The load’s frequency dependence is commonly
expressed by multiplying either the polynomial or exponential load model by a factor. An exponential static load model with voltage and frequency dependence is shown in (1) and (2)

\[ P = P_o \left( \frac{V}{V_o} \right)^{NP} \left( 1 + K_{PF} \Delta f_{\text{p.u.}} \right) \]  
\[ Q = Q_o \left( \frac{V}{V_o} \right)^{NQ} \left( 1 + K_{QF} \Delta f_{\text{p.u.}} \right) \]  

where \( V_o \) represents the initial operating voltage and \( P_o \) and \( Q_o \) represent the active and reactive power corresponding to the initial operating voltage. \( \Delta f_{\text{p.u.}} \) represents the deviation in frequency from the nominal frequency in per unit. \( V \) represents the operating voltage. \( NP, NQ, K_{PF}, \) and \( K_{QF} \) correspond to the parameters of the load model \([9]\). As previously discussed, constant RLC loads are commonly used for analyzing and testing islanding detection methods. Constant impedance loads are represented by setting \( NP = NQ = 2 \) and \( K_{PF} = K_{QF} = 0 \) in (1) and (2). Constant power and constant current loads could be represented by setting the exponentials to 0 and 1, respectively.

### III. System Under Study

The system, shown in Fig. 1, consists of a distribution network represented by a source behind impedance, a load that is voltage and frequency dependent and a 100 kW inverter-based DG. The DG interface control model presented in \([5]\) was implemented (refer to Table II). The DG is designed to operate as a constant power source with unity power factor operation.

Once islanding occurs, the island experiences a voltage dip due to the excessive loading on the island. The results show that the amount of voltage deviation is inversely proportional to the amount of active and reactive power mismatch. The NDZ of the OVP/UVP and OFP/UFP method decreases as the value of NP decreases. On the contrary, the steady-state frequency is independent on the value of NP. As the value of NP increases, it becomes harder to detect islanding for the same amount of active and reactive power mismatch. The NDZ of the OVP/UVP and OFP/UFP method decreases as the value of NP decreases. On the contrary, the steady-state frequency is independent on the value of NP. From Fig. 3, the frequency will deviate towards the load resonance frequency since the DG is designed to operate at unity power factor. It can be concluded that the voltage variation will depend on the amount of active power mismatch as well as the value of NP.

### IV. Effect of Load Parameters on System Frequency and Voltage

The system under study was modeled and simulated on PSCAD/EMTDC. The utility breaker, at the point of common coupling (PCC), was forced to open at \( t = 3 \) s to simulate an islanding condition. For the OVP/UVP and OFP/UFP method, the two important parameters that need to be monitored are the PCC voltage and frequency. The following subsections highlight the simulation results for each case study.

#### A. Case 1: Effect of NP on Islanding Detection

The parameter NP represents the load’s active power voltage dependence. In order to examine its effect on islanding, the parameter NP is varied while keeping all other load parameters constant (refer to Table I). Fig. 3 shows the PCC voltage and frequency waveforms during an islanding condition.

Once islanding occurs, the island experiences a voltage dip due to the excessive loading on the island. The results show that the amount of voltage deviation is inversely proportional to the parameter NP. As the value of NP increases, it becomes harder to detect islanding for the same amount of active and reactive power mismatch. The NDZ of the OVP/UVP and OFP/UFP method decreases as the value of NP decreases. On the contrary, the steady-state frequency is independent on the value of NP. From Fig. 3, the frequency will deviate towards the load resonance frequency since the DG is designed to operate at unity power factor. It can be concluded that the voltage variation will depend on the amount of active power mismatch as well as the value of NP.

#### B. Case 2: Effect of NQ on Islanding

The parameter NQ represents the load’s reactive power voltage dependence. The load’s inductance and capacitance will depend on the value of NQ. The parameter NQ and \( K_{QF} \)}
of $K_{PF}$. The voltage deviations will be dependent on frequency deviations due to the load’s active power dependence on frequency deviation. In other words, voltage deviations will be dependent on the amount of reactive power mismatch. It can be concluded that the voltage deviation is not only dependent on the active power mismatch but is also dependent on the amount of reactive power mismatch and the value of $K_{PF}$.

D. Case 4: Effect of $K_{QF}$ on Islanding

Finally, the parameter $K_{QF}$ is varied while fixing the remaining load parameters. Fig. 6 shows the PCC voltage and frequency waveforms during an islanding condition. The active and reactive power mismatch will result in voltage and frequency deviations. Similarly, the frequency deviation will depend on the load’s resonance frequency. The voltage variations are due to the load’s active power voltage and frequency dependence. The frequency and voltage variations are independent on the value of $K_{QF}$ for a DG operating at unity power factor.

V. NONDETECTION ZONES

Islanding detection methods are commonly evaluated by using the concept of NDZ. NDZ could be defined as the range of values of loading for which an islanding detection method would fail to detect islanding. The simulation results, in Section IV, show that the load’s voltage and frequency dependence have an effect on islanding detection. This, in turn, could have an impact on the NDZ of the OVP/UVP and OFP/UFP method. In order to derive a general formula for calculating the NDZ of the OVP/UVP and OFP/UFP method, the load’s RLC are expressed as follows:

\[ P = (1 + \Delta P)P_o \left( \frac{V}{V_o} \right)^{NP} \left( 1 + K_{PF} \Delta f_{p,u} \right) = \frac{V^2}{R} \]  
\[ Q_L = (Q_o + \Delta Q) \left( \frac{V}{V_o} \right)^{NQ} \left( 1 + K_{QF} \Delta f_{p,u} \right) = \frac{V^2}{\omega_0 L} \]  
\[ Q_C = Q_o \left( \frac{V}{V_o} \right)^{NQ} \left( 1 + K_{QF} \Delta f_{p,u} \right) = V^2 \omega_0 C \]
where $P_L, Q_L$, and $Q_C$ represent the load’s active, reactive (inductive), and reactive (capacitive) power per phase. $P_o, Q_o, V_o$, and $\omega_o$ represents the rated active and reactive power, rated voltage, and rated frequency. $\Delta P$ represents the active power mismatch in per unit. $\Delta Q$ represents the reactive power mismatch in vars. Since the DG is designed to supply zero reactive power, the reactive power mismatch equation could be written as

$$Q = 0 = \frac{V^2}{\omega L} - \omega^2 C \Delta Q$$  \hspace{1cm} (6)

where $\omega$ represents the operating frequency in radians per second. Substituting (4) and (5) in (6) and simplifying

$$\frac{\omega^2}{\omega_o^2} = 1 + \frac{\Delta Q}{Q_o},$$  \hspace{1cm} (7)

A mismatch in reactive power will result in a frequency deviation and (7) could be written in terms of $f$ (Hz) as follows:

$$f^2 = (f_o + \Delta f)^2 = f_o^2 + \frac{\Delta Q}{Q_o}$$  \hspace{1cm} (8)

where $f = f_o + \Delta f$ and $\Delta f$ represent the change in frequency from nominal frequency in hertz. The relation between the reactive power mismatch and frequency deviation is expressed in (9)

$$\Delta f_{\text{match}} = \frac{\Delta f}{f_o} = \sqrt{1 + \frac{\Delta Q}{Q_o}} - 1.$$  \hspace{1cm} (9)

Equation (9) highlights the fact that the load’s voltage and frequency dependence has no effect on the amount of frequency deviation. The frequency deviation, during an islanding condition, will only depend on the amount of reactive power mismatch. This could also be seen from the simulation results presented in the previous section where the frequency in all cases stabilizes at approximately 60.3 Hz. From (9), the calculated frequency deviation resulting from a 1% reactive power mismatch is 60.299 Hz. Thus, the mathematical calculations coincide with the simulation results.

In a similar manner, a mathematical expression for the active power mismatch is derived. Since the DG is designed to supply constant power, the load’s active power has to stabilize at a condition where the amount of active power supplied to the load is equal to the DG-rated active power as expressed in (10)

$$P_{DG} = P_o = (1 + \Delta P)P_o \left(\frac{V_o(1 + \Delta V_{\text{p.u.}})}{V_o}\right)^{NP} \times (1 + K_{PF} \Delta f_{\text{p.u.}})$$  \hspace{1cm} (10)

where $\Delta V$ represents the deviation in voltage in per unit. From (10), the voltage deviation will depend on the active power mismatch as well as the frequency deviation. Knowing that frequency deviations are a result of the reactive power mismatch, the voltage deviation could be expressed in terms of the active and reactive power mismatch by substituting (9) in (10)

$$\Delta P = \frac{1}{(1 + K_{PF} \left[\sqrt{1 + \frac{\Delta Q}{Q_o}} - 1\right])(1 + \Delta V_{\text{p.u.}})^{NP}} - 1.$$  \hspace{1cm} (11)

Equation (11) represents the general formula for calculating the voltage deviation during an islanding condition. For a 10% active power mismatch and 1% reactive power mismatch, the calculated voltage deviation using (11) is approximately 0.948 per unit with $NP$ and $K_{PF}$ set to 2. It can be seen from (11) that the voltage deviation, during an islanding condition, is dependent on $NP$ and $K_{PF}$. The results coincide with the simulation results presented in Section IV.

The NDZ of the OVP/UVP and OFP/UFP method is calculated by using (8) and (11). The upper and lower frequency thresholds are 60.5 Hz and 59.3 Hz, respectively. The upper and lower voltage thresholds are 1.1 p.u. and 0.88 p.u., respectively. Figs. 7 and 8 show the NDZ for different values of $K_{PF}$ and $NP$, respectively. The NDZ corresponding to path A3-B3-C3-D3 represents the NDZ for an island with constant RLC load and coincides with the results obtained in [6]. The remaining two paths: A1-B1-C1-D1 and A2-B2-C2-D2, represent the NDZ for the case where $K_{PF} = 5$ and $K_{PF} = 2$, respectively. The parameter $K_{PF}$ affects the NDZ and results in an increase in the amount of undetectable active power mismatch. For example, the maximum amount of undetectable active power mismatch for loads with $K_{PF} = 5$ is approximately 36% as opposed to 29% for the constant RLC load case (refer to Fig. 7).

In addition, the NDZ for a load with $NP = 2$ (path C1-C2-C3-C4), $NP = 1.5$ (path B1-B2-B3-B4) and $NP = 1$ (path A1-A2-A3-A4) is presented in Fig. 8. The NDZ of the OVP/UVP and OFP/UFP method decreases as the value of $NP$ decreases for a fixed value of $K_{PF}$ ($K_{PF}$ set to 5). It can be seen from the results that the load’s active power voltage and frequency dependence has an effect on the NDZ of the OVP/UVP and OFP/UFP method. The skew in the NDZ curves arises from the nonlinear relationship between the active and reactive power mismatch (refer to (11)), resulting from the load’s frequency dependence.

The NDZ presented in Figs. 7 and 8 is based on the mathematical formula presented in (11). The NDZ was determined by repeated simulation by using PSCAD/EMTDC for the various cases studied. Fig. 9 presents the simulated NDZ with $K_{PF} =$
$K_{PF} = 2$ and $K_{PF} = 5$ for a constant power-controlled interface. By comparing Figs. 7 and 9, it can be seen that the simulation results closely match the results obtained by using the mathematical formula.

In this section, we further explore the impacts of the load’s voltage and frequency dependence on islanding by investigating another type of DG interface: “the constant current controlled interface.” The constant current-controlled interface is similar to the interface presented in Fig. 2 but with $I_{dref}$ and $I_{pref}$ set to a fixed value [6]. In a similar manner, the NDZ is derived mathematically in terms of the active and reactive power mismatch. The relation between the active power mismatch and frequency deviation is identical to the one expressed in (9). The active power mismatch expression could be derived by equating the DG-rated active power output to the load’s active power as shown in (12)

$$P_{DG} = VI_o = (1 + \Delta P)P_o \left( \frac{V_o(1 + \Delta V_{pum})}{V_o} \right)^{NP} \times (1 + K_{PF}\Delta f_{pum}) \quad (12)$$

where $I_o$ represents the rated power output of the DG. As seen in (12), the DG output power is expressed in terms of the DG-rated output current. By rearranging and performing further simplifications

$$V_o(1 + \Delta V_{pum})I_oV_o = (1 + \Delta P)P_o \left( \frac{V_o(1 + \Delta V_{pum})}{V_o} \right)^{NP} \times (1 + K_{PF}\Delta f_{pum})V_o \quad (13)$$

$$V_o(1 + \Delta V_{pum})P_o = (1 + \Delta P)P_o \left( \frac{V_o(1 + \Delta V_{pum})}{V_o} \right)^{NP} \times (1 + K_{PF}\Delta f_{pum})V_o \quad (14)$$

$$1 = (1 + \Delta P)(1 + \Delta V_{pum})^{NP-1} \times (1 + K_{PF}\Delta f_{pum}) \quad (15)$$

$$\Delta P = \frac{1}{\left( 1 + K_{pf} \left[ \sqrt{1 + \frac{\Delta Q}{Q_o}} - 1 \right] \right)}(1 + \Delta V_{pum})^{NP-1} - 1 \quad (16)$$
Equation (16) presents the general equation for calculating the active power mismatch for a constant current-controlled DG. Similarly, for a constant current-controlled DG designed to operate at unity power factor, the parameters NP and \( K_{PF} \) have no effect on the NDZ of the OVP/UVP and OFP/UFP method. The NDZ for a load with \( K_{PF} = 5 \) (path A3-B3-C3-D3), \( K_{PF} = 2 \) (path A2-B2-C2-D2) and \( K_{PF} = 0 \) (path A1-B1-C1-D1) is presented in Fig. 10. The NDZ for the case where \( K_{PF} = 0 \) coincides with the simulation results obtained in [6]. Similarly, the parameter \( K_{PF} \) results in an increase in the amount of undetectable active power mismatch. The NDZ for a load with \( NP = 2 \) (path A3-B3-C3-D3) and \( NP = 1.5 \) (path A2-B2-C2-D2) is presented in Fig. 11. Similarly, it can be seen that \( K_{PF} \) and NP affect the NDZ. As the value of NP increases, the NDZ increases. For the case where \( NP = 1 \), the NDZ is negligible. For the same value of NP, the constant current-controlled DG has a much smaller NDZ than the constant power controlled DG.

Similarly, the analytical NDZ shown in Fig. 10 was validated by performing repeated simulations for various loading conditions. Fig. 12 presents the simulated NDZ with \( K_{PF} = 0 \), \( K_{PF} = 2 \) and \( K_{PF} = 5 \) for a constant current-controlled DG interface. Similarly, by comparing the calculated and simulated NDZ, it can be seen that the results obtained by using the two different approaches coincide with each other.

**VI. CONCLUSION**

This paper analyzes the performance of the OVP/UVP and OFP/UFP method during an islanding condition with voltage- and frequency-dependent loads. The simulation results show that the DG performance during an islanding condition will depend to a great extent on the load’s voltage and frequency parameters. The mathematical formula, derived for calculating the NDZ, shows that the OVP/UVP and OFP/UFP method is dependent on the load’s active power voltage and frequency dependency parameters and is independent on the load’s reactive power voltage and frequency dependence. Frequency-dependent loads have larger active power mismatch limits than constant RLC loads and should be considered when testing the OVP/UVP and OFP/UFP method. The results show that constant RLC loads do not necessarily constitute the worst loading condition for islanding studies.

**REFERENCES**


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