D6.5.19 Protection of DG from the power system point of view

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***Abstract*—All distributed generating units need to be equipped with some kind of loss of mains protection (LOM) scheme which is meant for avoiding unintentional islanding. Large amount of novel LOM protection algorithms have been presented in the literature in the recent years. Especially active LOM protection schemes, which are based on detecting islanding by deliberate injection of small disturbances, have been emphasized. It has been observed that active LOM protection schemes may not function properly when multiple converter based DG units are connected to the same islanded circuit. However, studies analyzing the behavior of active LOM protection in an islanded circuit with both directly connected and converter connected generators are very scarce. This paper tries to fill this gap by analyzing the effect of mixed types of DG on the performance of reactive power variation (RPV) based islanding detection. Simulations were performed in order to verify the expected behavior and the results were examined analytically. The results indicate that the performance of RPV based islanding detection is significantly degraded when the islanded circuit contains both converter- and directly connected generating units.**

***Index Terms*—Distributed generation (DG), inverters, islanding detection, protection, synchronous generators**

I. Introduction

THE RAPIDLY increasing amount of distributed generation (DG) units is raising concerns related the functioning of distribution network protection. Especially challenges related loss of mains (LOM) protection have been studied widely in the recent years. LOM protection, which is also known as anti-islanding protection, is meant for ensuring that no generating units are left feeding customer loads in islanded circuits. The avoidance of unintentional islanding is important due to the associated safety hazards for utility personnel but also because DG units and network components may be damaged as a consequence of unsynchronized reclosing of the islanded circuit. In addition, customer loads in the islanded circuit may be damaged due to poor power quality.

LOM protection methods can be divided into passive, active and communication based methods. Lately active LOM detection methods have especially received remarkable attention due to the fact that many of them are claimed to be capable of detecting islanding even when there is no power mismatch between production and consumption in the islanded circuit [1]–[3]. However, it has been observed that many active LOM protection methods may not function properly when multiple inverter based units are connected to the islanded circuit [4], [5]. This is especially the case when the islanded circuit contains both converter connected DG and directly connected synchronous generators [6]. It was shown with the help of non-detection zone (NDZ) mappings in [6] that in theory active LOM protection schemes may not function properly due to the presence of a synchronous generator. This paper continues the studies presented in [6] by examining how a very aggressively configured reactive power injection based active LOM protection is affected when the islanded circuit contains mixed types of DG. This problematic issue is analyzed both theoretically and with simulations. For brevity, the contribution of this paper is not to present a novel LOM protection method but to study a potential risk related to the utilization of active LOM protection methods.

II. Loss of Mains Protection

Islanding refers to a situation where a network area including customer loads and DG is separated from the main grid. Unintentional islanding is forbidden, and all DG units thus need to be equipped with a LOM protection scheme which ensures that unintentional islanding does not occur. According to the IEEE 1547 standard, islanding should be detected and ceased within 2 s at maximum [7]. However, considerably faster detection may be required if fast automatic reclosing (AR) is utilized on the feeder where the DG unit(s) are connected. This is because DG units need to be disconnected during the open time of the circuit breaker performing the AR sequence in order to avoid the risk of unsynchronized reclosing. Moreover, for the successful use of AR it is necessary that DG units on the feeder are disconnected well before the reclosing of the feeder. This is because even though the fault arc extinguishes when the line is de-energized, there has to be sufficiently large period of time for the ionized gasses formed in the fault arc to disperse. Otherwise, the fault arc easily reignites when the line is again energized. One option for avoiding these fast AR related problems is to give up using fast AR. However, this is highly undesirable from electricity supply reliability point of view. For instance, 56 percent of faults on Finnish overhead distribution lines were cleared with fast AR in 2012 [8]. It is therefore highly advantageous that LOM protection is able to detect islanding in a time that is compatible with the requirements set by the use of fast AR, say from 100ms to 500ms depending on the utilized open time of fast AR.

A. Non-Detection Zone

Most LOM protection methods are based on detecting the changes in system quantities such as voltage and frequency. These changes, which usually take place when islanding occurs, are mainly caused by the imbalance between the production and consumption of real- and reactive power in the island. There is, however, a risk that this imbalance is so small that the transition to island mode does not cause any of the quantities measured by a LOM relay to drift out of the preset limits. In cases like this, LOM protection fails to detect islanding. This blind area of LOM protection in the surroundings of the production- consumption equilibrium is called the NDZ. The grey areas in Fig. 1 illustrate the conceptual shape of the NDZ for traditional overvoltage- (OVP) / undervoltage (UVP) and overfrequency- (OFP) / underfrequency based LOM protection (UFP). As the left side of Fig. 1 illustrates, reactive power imbalance (ΔQ) is mainly related to UVP/ OVP limits and active power imbalance (ΔP) mainly to UFP/ OFP limits, when the islanded network is maintained by a directly coupled synchronous generator [9]. However, when the islanded circuit is fed only by a converter connected DG unit, reactive power imbalance mainly determines frequency, whereas active power imbalance mainly determines voltages as illustrated in the right side of Fig. 1. [10] The exact shape and size of the NDZ is, nevertheless, dependent on the factors such as control mode of the islanded DG, inertial mass of generators and characteristics of the load.

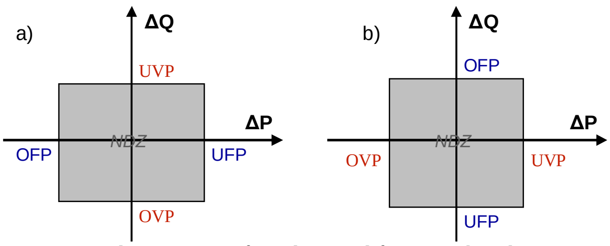

Fig. 1. Non-detection zone for voltage and frequency based LOM protection when the DG unit in question is a) directly connected b) converter coupled.

The relations between active- and reactive power with voltage and frequency can better be understood by examining a case where an inverter is feeding a parallel load connected to the circuit as shown in Fig. 2. During islanding, the active- and reactive power consumed by the load have to match with the production of the inverter as expressed in (1) and (2), where V refers to line to line voltage of the circuit and the subscripts INV and load refer to inverter and load. Thus, from (1) it can be seen that voltage is proportional to active power. Consequently, assuming that voltage is determined by P_{INV} and R, a clear relation between reactive power and frequency can be seen from (2). Frequency f will deviate to such value that the reactive power consumed by the load matches with the production of the islanded DG in the island. This can be expressed as in (2).

$$P_{\mathrm{INV}} = \frac{V^2}{R} = P_{\mathrm{Load}} \tag{1}$$

$$Q_{\mathrm{Load}} = V^2\left[\frac{1}{2\pi fL - \frac{1}{2\pi fC}}\right] = RP_{\mathrm{Load}}\left[\frac{1}{2\pi fL - \frac{1}{2\pi fC}}\right] = Q_{\mathrm{INV}} \tag{2}$$

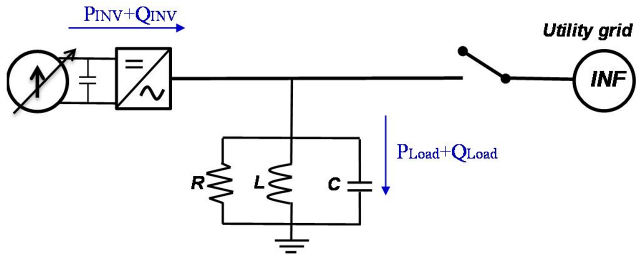

Fig. 2. A simple circuit for islanding detection analysis.

However, if the inverter based DG unit is replaced by a directly connected synchronous generator, the frequency is determined by the speed of the generator. The factors determining the speed of the generator can be analyzed with the help of the swing equation (3). It is noteworthy that - windage, friction and iron-loss torque are ignored in (3):

$$P_{\mathrm{m}} - P_{\mathrm{e}} = \frac{GH}{\pi f_{\mathrm{nom}}}\frac{d^2\delta}{dt^2} \tag{3}$$

where P_{m} is the mechanical power input to the generator, P_{e} is the electrical power output of the generator, G refers to the nominal power of the generator, f_{nom} is the nominal system frequency, H refers to inertia constant and δ is the power angle (i.e., rotor angular displacement from synchronously rotating reference) [11]. The term $d^2\delta / dt^2$ thus represents the angular acceleration of the generator. If there is more active power load in the island in comparison with the active power produced by the generator before the islanding, the generator will decelerate. Respectively, the generator will accelerate if the active power demand in the islanded circuit is less than the power produced by the generator before the islanding. Islanding detection related studies are dealing with short time frames only and consequently, the mechanical power input P_{m} can be assumed to be constant.

B. Islanding detection methods

LOM detection methods can be divided into communication based methods, local passive methods and local active methods. Passive methods are based on locally measuring certain system quantities, such as voltage and frequency. The idea behind these methods is that some changes in the measured quantities usually occur during the transition to islanding. Passive methods are popular due to their low cost and applicability to all DG units. The downside of these methods is that most of them have a large NDZ.

Active LOM protection schemes are based on detecting LOM by constantly injecting small perturbations and measuring the response of the system. The idea behind this is that the system quantities can only be manipulated during islanding. [12] Some active detection schemes can even detect balanced islanding, but usually at the cost of degraded power quality. Active and passive methods can also be combined together. The combination makes it possible to reduce the degrading effect on power quality caused by the active method if the active method is activated only when the passive method suspects islanding. The utilization of two sequential methods may, however, result to slower detection of islanding [13].

Communication based LOM protection schemes are based on somehow signaling the islanded DG units. These schemes are immune to the NDZ problem because they are not based on local measurements. However, they are typically more costly than other methods and also vulnerable to communication failures. Moreover, a local LOM protection method is always needed for backup protection. [12]

C. Reactive power variation (RPV) based LOM protection

In the studies of this paper, a reactive power injection based LOM protection method was chosen. This method is set to feed/absorb reactive power proportionally to the deviation of measured frequency from the nominal frequency. Equation (4) expresses the basic idea of the used LOM protection method.

$$I_{\mathrm{q,INV}} = k(f_{\mathrm{nom}} - f_{\mathrm{meas}}) \tag{4}$$

where k refers to the chosen gain value, f_{nom} to the nominal frequency and f_{meas} to the measured frequency. No dead band was used in these studies although in reality network operators may find it more favorable to apply a small frequency error dead band in order to reduce the power quality problems. However, for the purpose of this paper it is more suitable to have no dead band, and thus make the islanding detection method more effective. The voltage frequency protection thresholds were chosen to be 48Hz for underfrequency and 51Hz for overfrequency limit in the studies of this paper.

III. Simulation models

A. Network model

A simple overhead line medium voltage network was modeled with the help of PSCAD software for these studies. The model, which is depicted in Fig. 3, consists of one medium voltage feeder that is fed through a HV/MV transformer from 110kV network. The feeders are modelled with the help of PI-line sections which are available in the PSCAD component library. Two RLC loads were connected along the feeder as shown in Fig. 3. The R, L and C values of these parallel connected RLC loads were chosen so that the quality factor (Q_{f}) of the loads was 2.5 at each chosen level of active and reactive power consumption as suggested in [14]. Quality factor of a parallel RLC load can be represented as two pi times the ratio of the maximum stored energy to the energy dissipated per cycle at a given frequency [14]. In mathematical terms, Q_{f} can be presented as in (5). The R, L and C values of the load were calculated from (6) – (8) thus taking the quality factor of the load (5) into account.

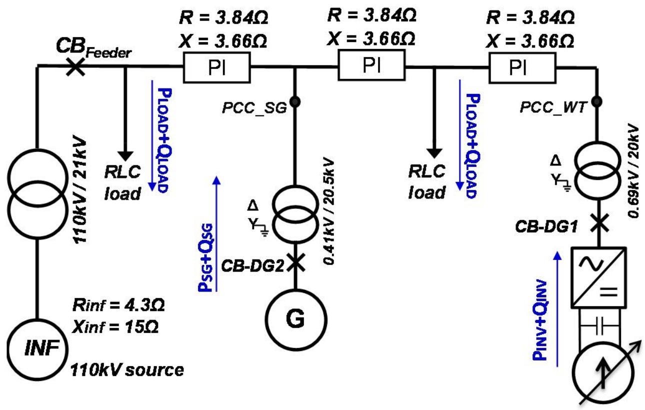

Fig. 3. The general structure of the utilized simulation model.

$$Q_{\mathrm{f}} = \frac{R}{\omega_0 L} = \omega_0 C = R\sqrt{\frac{C}{L}} \tag{5}$$

$$R = \frac{V^2}{P_{\mathrm{Load}}} \tag{6}$$

$$C = \frac{V^2 Q_{\mathrm{f}}^2 + \sqrt{V^4 Q_{Load}^4 + 4Q_{Load}^2 Q_{\mathrm{f}}^2 R^2}}{2Q_{Load}\,\omega R^2} \tag{7}$$

$$L = \frac{CR^2}{Q_{\mathrm{f}}^2} \tag{8}$$

B. DG unit models

Two DG units were connected along the feeder as shown in Fig. 3. The first unit was a 1450kVA rated directly connected synchronous generator which was controlled so that the active and the reactive power references were constant. Before the moment of islanding, the active and reactive power measured from the MV side connection point (PCC_SG in Fig. 3) of this DG unit, were 875kW and 10kVar. The inertia constant of the generator was 2.0s. The other DG unit was a 500kVA rated full converter connected wind turbine (FCWT) which is presented in [15]. The control system, LCL filter and network side converter parameters of this model are the same as in [15] with the exception that the phase locked loop model from the PSCAD library is used as a synchronization method.

The reference of the reactive current was set so that the reactive power measured from the point of common coupling (PCC_WT in Fig. 3) was 0kVar during nominal operation (500kW). The FCWT was equipped with a RPV based LOM protection whose functioning can be represented by (4). A gain value 300A/Hz was used in these studies for the RPV droop. However, the output current of the converter was limited to 1.5 times the nominal current.

IV. Simulation Results

This chapter presents the simulation results of the LOM protections studies which were obtained using the PSCAD/EMTDC. Islanding was set to occur at time 10.0s in all the presented simulation cases for ensuring that everything had stabilized before islanding took place. In the first subchapter, a case where only the converter connected WT was connected to the network is presented. After this, a case which illustrates how the addition of RPV algorithm improves the performance of LOM protection is presented. In the second subchapter, both DG units were connected to the circuit as shown in Fig. 3 and the simulations were repeated first without the RPV based LOM protection and then with the RPV method. Finally, a third subchapter is given in order to present a potential operational risk related to RPV method.

A. Only Converter Connected DG

In the first simulation case, a PSCAD simulation where only the full converter connected wind turbine (FCWT) was connected was performed. The RPV based LOM protection was disabled by setting the Iq gain to 0.01A/Hz. Graphs presenting voltage magnitude and frequency are shown in Fig. 4. The consumption of the two parallel RLC loads was set to match production closely ($|\Delta P_{Feeder}|$<3kW & $|\Delta Q_{Feeder}|$<3kVar). Islanding was set to occur at the time 10.0s. As it can be seen from Fig. 4, voltage magnitude and frequency stay close to their nominal values and islanding could not have been detected by simply monitoring these quantities.

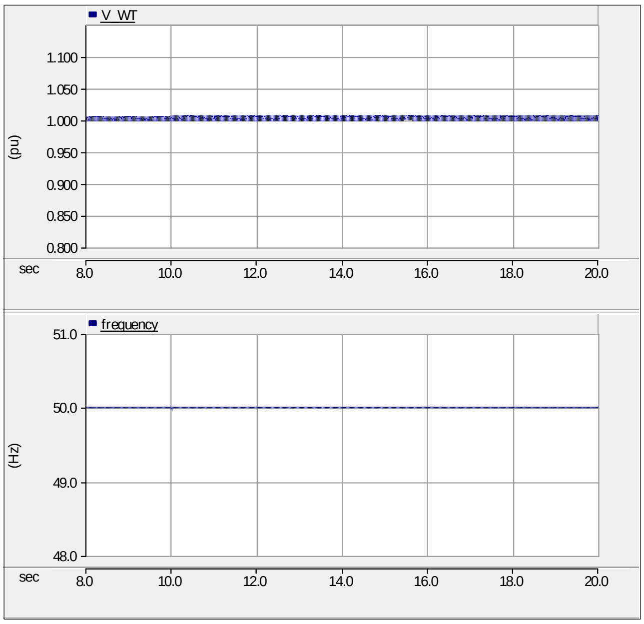

Fig. 4. Voltage magnitude and frequency when only the FCWT was connected and the Iq gain of the RPV method was set to 0.01A/Hz.

In the following case, the Iq gain was set to 300A/Hz and the previous simulation was repeated. Now frequency dropped below 48Hz in 164ms as shown in Fig. 5. The graphs in Fig. 5 present voltage frequency, the measured value (Iq_meas) for the q-component of the inverter current, voltage magnitude at the connection point of the FCWT and the active- and reactive power output of the inverter. It can be seen from Fig. 5 that the Iq value is approximately -13A already during normal state. The Iq is controlled to this value in order to compensate the effect of the LCL filter capacitor. At the time 10.17s the Iq reaches its maximum value 470A to which it is limited.

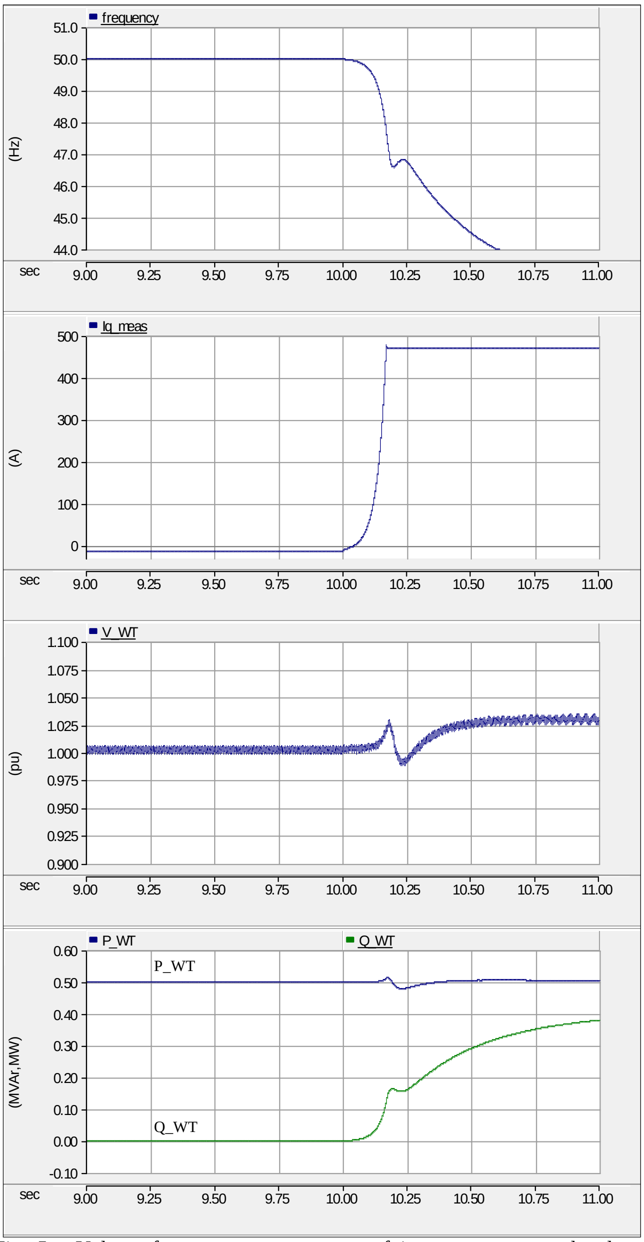

Fig. 5. Voltage frequency, q-component of inverter current and voltage magnitude when only the FCWT was connected and the Iq gain value of the RPV method was set to 300A/Hz.

B. Mixed Types of DG in the islanded circuit

In the following, both DG units were connected to the network and the simulations were repeated. The power flowing from the main grid was set to a negligible value ($|\Delta P_{Feeder}|$<3kW & $|\Delta Q_{Feeder}|$<3kVar). Firstly, the Iq gain value was set to 0.01A/Hz, i.e., the active LOM detection method was disabled. Both voltage and frequency stayed close to their nominal values as shown in Fig. 6, which represents the voltages from the PCCs of the DG units and the frequency. Islanding could not thus have been detected with simple voltage magnitude and frequency based LOM detection.

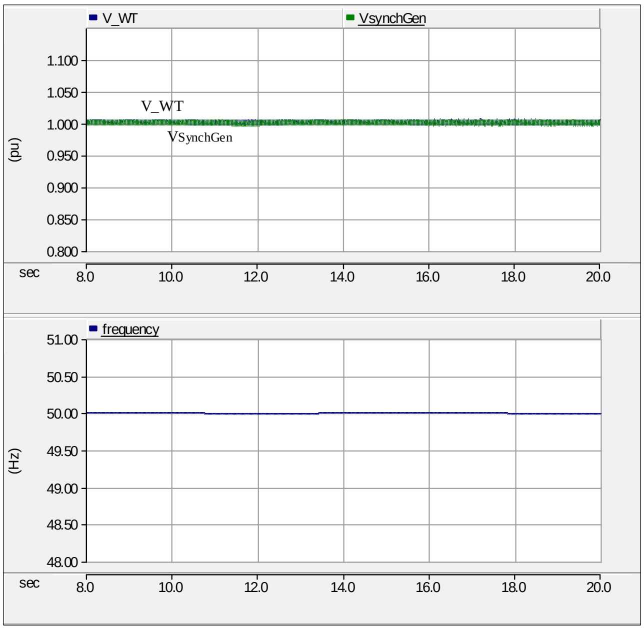

Fig. 6. Voltage magnitude of the PCCs of the DG units and voltage frequency

Now, in order to make the detection of islanding possible, the Iq gain value was set to 300A/Hz and the previous simulation was repeated. The graphs in Fig. 7 represent voltage frequency, q-component current of the inverter, voltage magnitudes from the PCCs of the DG units and the active- and reactive power values of the inverter (subscript WT), synchronous generator (subscript SG), and the two loads (subscript load_tot). The addition of the RPV method helped to drive the frequency out of the limits as it can be seen from Fig. 7. However, it took 5680ms to bring the frequency out of the thresholds. This is remarkably longer than the respective time (164ms) in the case where the island was sustained only by the converter connected DG unit. These simulation results thus clearly show that the performance of RPV based active LOM detection method is significantly degraded due to the addition of the synchronous generator to the islanded circuit.

The reason for this outcome is that the design principle of RPV method assumes that frequency can be manipulated by feeding or consuming reactive power. However, the presence of a synchronous generator partially invalidates this assumption since frequency is tied to the speed of the generator. RPV, nevertheless, still indirectly affects frequency because the RPV affects the voltages in the islanded circuit. In order to better understand this, let us rewrite equations (1) – (3) for the case where both DG units are present in the islanded circuit. In this case, the electrical output power of the synchronous generator (P_e) can be expressed as:

$$P_e = \frac{V^2}{R} - P_{INV} \quad (9)$$

This is the active power that the synchronous generator is able to feed to the islanded circuit. With the help of (9), we can now rewrite (3) for the mixed DG case:

$$P_m - \left(\frac{V^2}{R} - P_{INV}\right) = \frac{GH}{\pi f_{nom}} \frac{d^2\delta}{dt^2} \quad (10)$$

Respectively, reactive power production and consumption have to match each other and (2) can thus be rewritten as:

$$Q_{Load} = V^2 \left[\frac{1}{2\pi f L - \frac{1}{2\pi f C}}\right] = Q_{SG} + Q_{INV} \quad (11)$$

Now, when looking at (11), one has to bear in mind that frequency is now tied to the speed of the synchronous generator. The changes in the speed, i.e. the acceleration of the generator can be described by the term $d^2\delta/dt^2$ in (10). Thus, when the RPV controls the reactive power output of the inverter to change, it actually affects the voltage. However, a change in voltage changes the active power load and thereby the electrical output power which the synchronous generator is able to feed as stated by (9). This, in turn, causes the relation between the mechanical power that is fed to the generator and electrical output power of the generator to change as stated by (10). As a consequence, the term $d^2\delta/dt^2$ becomes positive in case if voltage reduces, or negative if voltage increases and the machine thus accelerates or decelerates.

The above given reasoning can be seen from Fig. 7 also. Due to a slight deviation or swinging in frequency, the RPV controls the inverter to feed reactive power. As a result of the injected reactive power, the voltages at the PCCs of the DG units begin to increase. The greatest increase in voltage occurs at the PCC of the inverter since the inverter is the source of the additional reactive power. An increase in voltages naturally results to an increase in active power load and consequently, the synchronous generator is forced to feed the required additional active power. This additional energy is taken from the rotational energy of the synchronous generator and the machine therefore begins to decelerate thus causing the frequency to decrease. However, this indirect the effect of RPV on frequency is considerably less effective than the direct effect in a case with only inverter based DG. This is mostly because the inertial mass of the machine slows down changes in generator speed.

The effect of the inertia constant of the synchronous generator on the studied LOM protection was analysed by repeating the simulation presented in Fig. 7 several times while changing the inertia constant. The graph in Fig. 8 illustrates how an increase in the value of the inertia constant degrades the performance of the RPV based LOM protection method. Note that an additional 100ms extra delay was added to the times in which the frequency drifted out of the limits in order to model a typical time delay of frequency relays. Also note that the original inertia constant value was 2.0s.

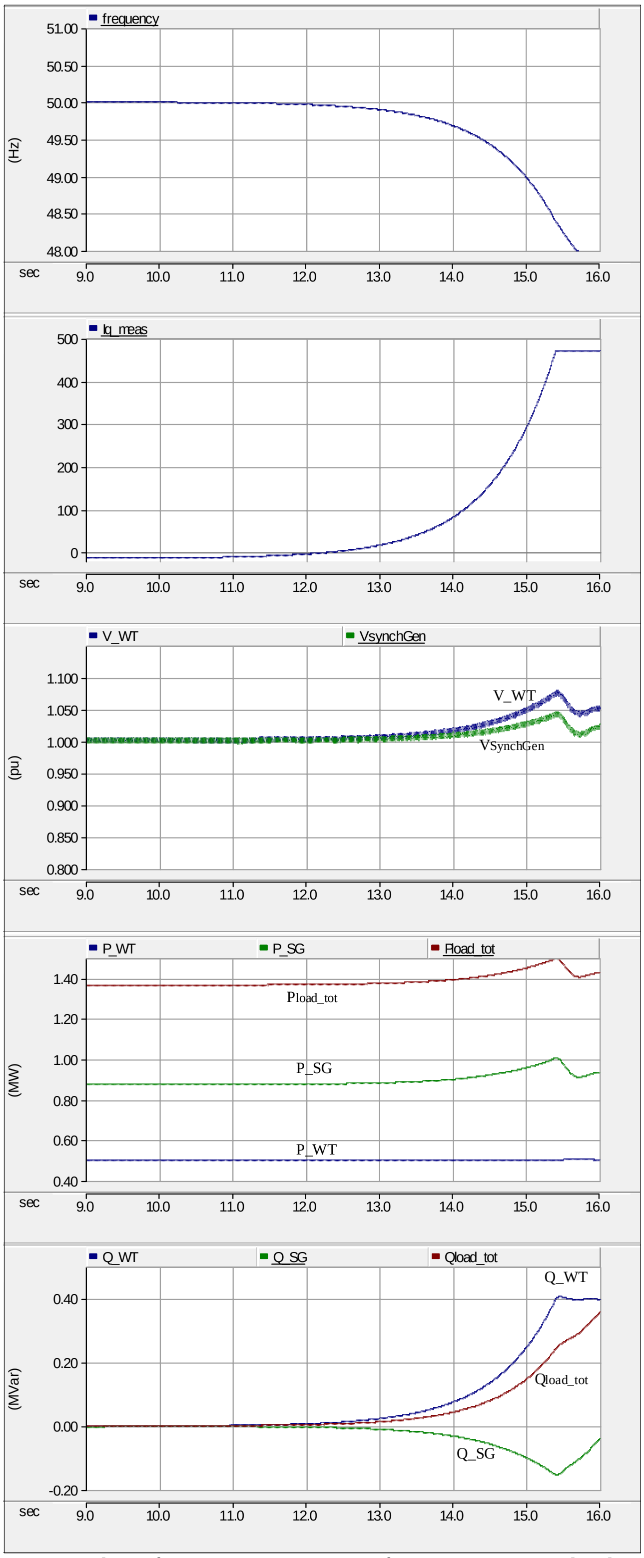

Fig. 7. Voltage frequency, q-component of inverter current and voltage magnitude when both DG units were connected in parallel and the frequency droop Iq gain value was set to 300A/Hz.

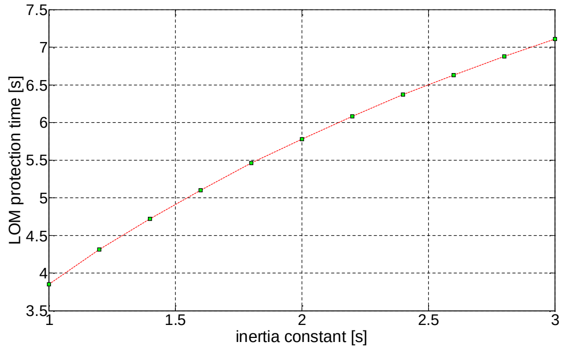

Fig. 8. The effect of inertia constant of synchronous generator on LOM detection.

A clear relation exists between the value of the inertia constant and the islanding detection time as Fig. 8 shows. This is in line with (10), since for a certain difference between mechanical input power to the generator (Pm) and the electrical power produced (Pe), the larger the inertia constant value H, the smaller is the value of the change of the generator speed ($d^2\delta/dt^2$). In other words, the higher the inertia constant, the slower the generator responds a certain difference between active power input and output.

It is noteworthy that according to (10), the rating of the generator *G* has a similar kind of effect on the acceleration of the machine as the inertia constant *H*. However, synchronous generator based DG units have typically larger ratings than converter based DG units. Thus, the scenario simulated in this paper represents a rather typical case. It is expectable that converter based DG units will be more common compared to directly connected synchronous generators. However, there are typically switches all around the network and many different sizes of power islands can thus be formed. Small converters connected to LV network may thus, for instance, form an island with a synchronous generator connected to MV network.

This problematic issue related to the mixed DG case is probably not only limited to RPV based LOM protection schemes but other frequency drifting based active LOM detection methods may also be similarly affected by the presence of synchronous generators. However, the verification of this requires more studies. This risk should be somehow taken into account in the design of active LOM protection schemes.

C. An operational risk related to RPV algorithm

RPV based LOM protection may actually have a degrading effect on passive voltage magnitude and frequency based LOM protection in certain conditions. Such a situation may occur when there is deficiency of both active power and reactive power in an islanded circuit containing both a directly connected synchronous generator and a converter connected DG unit. In a situation like this, both frequency and voltage will initially start to decrease as stated by (9) – (11). As a consequence to a frequency lower than the nominal, the RPV algorithm controls the inverter to feed reactive power.

However, instead of hastening the islanding detection, the injected reactive power may actually have a stabilizing effect on the islanded circuit which initially was lacking reactive power. A simulation case is presented in the following in order to illustrate this potential risk. The load was adjusted so that the active- and reactive power flowing to the feeder before the moment of islanding were 64kW and 60kVar. First the RPV based LOM protection was disabled and the case was simulated. In this case, frequency reaches the overfrequency limit 51Hz in 4.77s as shown in Fig. 9. As it can be seen, frequency first decreases slightly but then due to the effect of the rotating machine, swings towards overfrequency.

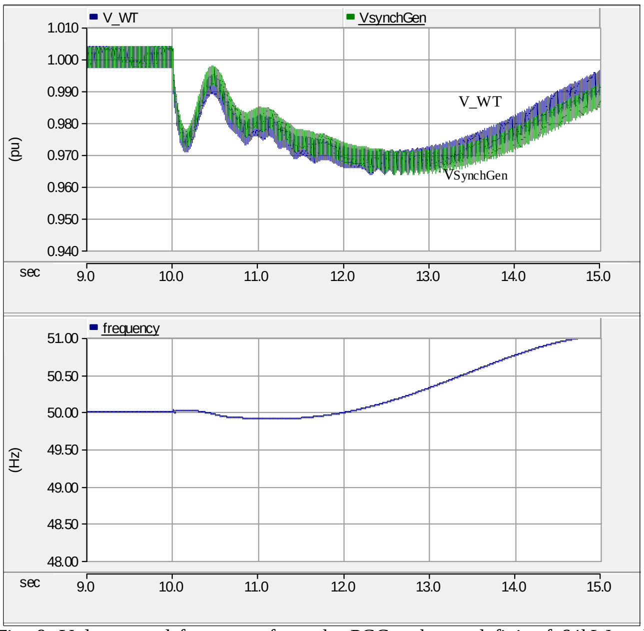

Fig. 9. Voltages and frequency from the PCCs when a deficit of 64kW and 60kVar was present before the islanding. The RPV method was disabled.

In the following case, the RPV method was activated with the 300A/Hz gain setting and the previous simulation case was repeated. The time for the frequency to drift out of limits increased to 6.32s as illustrated in Fig. 10. The reason for the poor performance of RPV algorithm in this case is caused by the swinging of the synchronous generator and the consequent response of the RPV algorithm.

As it can be seen from Fig. 10, frequency initially increases slightly after which it swings towards underfrequency, until finally a swing towards overfrequency causes the frequency to reach the overfrequency limit. The consequent response of RPV causes a large reactive power injection during the swing towards underfrequency. However, instead of improving the situation, the injected reactive power actually balances the islanded circuit which initially was lacking reactive power. This naturally degrades the functioning of LOM protection. A similar malfunctioning risk of RPV algorithm as the one presented above exists when there is surplus of both active- and reactive power in the islanded circuit prior to the islanding. It is noteworthy that the potential risk presented in this subchapter is likely to occur only when the power imbalance before the islanding is of minor scale and the proportions between active- and reactive power imbalance are proper for the phenomenon. The reason for this phenomenon to occur only when the power imbalance is rather small is that the first swing in frequency seen in Fig. 10 can be large enough to lead to under/over frequency if the initial power imbalance is large.

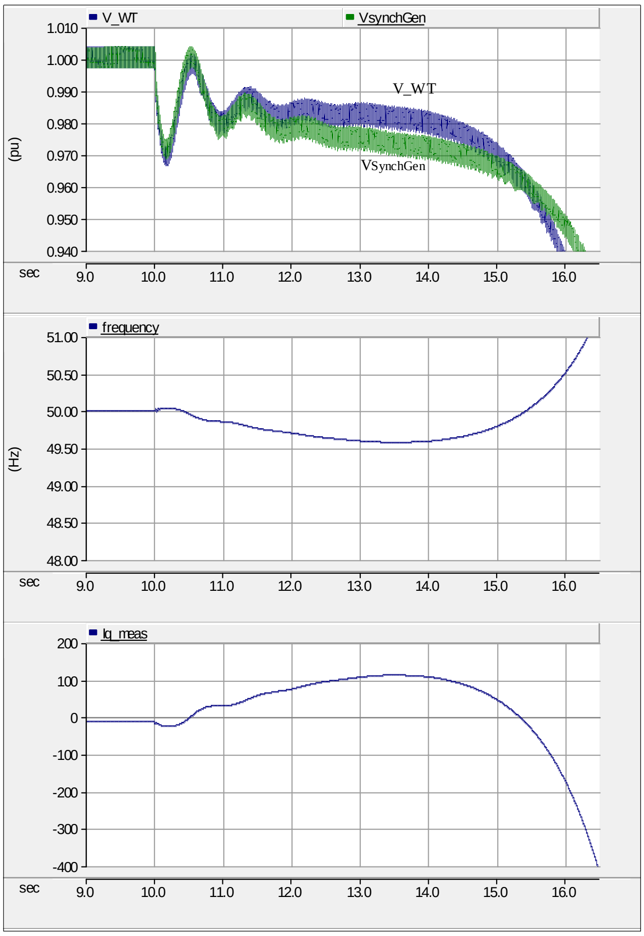

Fig. 10. Voltages and frequency from the PCCs when a deficit of 64kW and 60kVar was present before the islanding. The Iq gain was set to 300A/Hz.

V. Discussion

The simulation results presented in the previous chapter indicate that the performance of reactive power injection based active islanding detection methods can become significantly degraded when the islanded circuit contains a directly connected synchronous generator. Utility protection engineers should take this into account if they are planning to use active LOM protection methods. One option for avoiding this problem would be to equip the synchronous generators with a transfer trip type communication based LOM protection scheme. It is also noteworthy that the synchronous generator was only equipped with basic voltage magnitude and frequency based LOM protection in the studies of this paper and the problem could have been mitigated to some extent by using more effective LOM protection functions for the synchronous generator as well.

With regard to the potential risk related to RPV method that was presented in the previous chapter, it should be kept in mind that power system frequency is not exactly at nominal value all the time. In fact, grid frequency typically varies slightly even during normal operating conditions. Thus, DG units equipped with RPV based islanding detection methods are typically feeding/consuming reactive power unless an appropriate deadband is utilized. Additionally, the speed of a directly connected synchronous generator will be proportional to the system frequency provided that the system is in a stable state. Now, if a circuit containing both inverter and directly connected synchronous generator based DG suddenly becomes islanded when the system frequency is already less than nominal, the speed of the synchronous generator is less than the nominal also. Consequently, the RPV based LOM protection is already controlling the inverter to produce reactive power (if no deadband is used). However, there is most likely some amount of inductive load in the islanded circuit. Due to this, LOM protection may actually be balancing the reactive power imbalance.

VI. Conclusion

This paper studied the performance of RPV based LOM protection in circuits containing both converter connected DG and directly coupled synchronous generator based DG. The utilized RPV method was configured to be very aggressive which was also verified by simulations. The aggressive settings were chosen in order to show the severity of the impact of directly connected synchronous generators on the performance of RPV based LOM protection.

The simulation studies indicated that the utilized active LOM protection method was highly effective when the islanded circuit was sustained only by a converter connected DG unit. However, when a synchronous generator was connected to the same islanded circuit, the performance of the LOM protection method was degraded significantly. This was expectable because the design principle of reactive power injection method assumes that frequency can be manipulated by feeding reactive power. However, the presence of a synchronous generator partially invalidates this assumption. It is likely that other frequency drifting based LOM protection methods are also affected by this phenomenon. However, the verification of this requires further studies.

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