SENSITIVITY ANALYSIS OF FREQUENCY AND VOLTAGE STABILITY IN ISLANDED MICROGRID

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ABSTRACT

This paper studies the voltage and frequency stability of an islanded microgrid and the sensitivity of these quantities to certain changes in system configuration. In conventional power systems the system frequency is coupled with the rotor speed of the directly grid connected large synchronous generators and power unbalance can be seen as changed system frequency. But in an islanded microgrid it is possible that all generation units are connected to grid via converters and there is no inertia of rotating masses to affect the frequency. In that case the frequency has to be created by a power electronic device and the frequency is more of less fixed and power unbalance cannot be detected in the classical way. The studied urban low voltage (LV) network based microgrid consists of three converters and one synchronous generator based distributed generation (DG) units. The studies are made with PSCAD simulation software.

INTRODUCTION

Microgrids can be defined as distribution systems with DG units, energy storages and controllable loads, which can be operated either in interconnected mode, which means that the microgrid operates in parallel with the distribution grid, or in islanded mode, where the connection to the grid is switched off. Transition to islanded mode (islanding) may take place due to faults or intentional switching events. After islanding the microgrid operates autonomously with energy storages and controllable loads. The advantage for the grid is that microgrid can be seen as a single dispatchable load and from the customer point of view, microgrid meets local needs for power (and heat) and enhances local reliability and power quality. [1], [2]

In this paper the voltage and frequency stability of an islanded microgrid and the sensitivity of these quantities to certain changes in system configuration is studied. The studied urban low voltage (LV) network based microgrid consists of three converter and one synchronous generator (SG) based distributed generation (DG) units. The load in the microgrid consists of eight passive loads.

The results from simulations show how different control strategies and modulation methods of converters (Pulse width, PWM, hysteresis and space vector modulation, SVM) affect to frequency, voltage total harmonic distortion (THD) and rotor speed of synchronous generator in islanded microgrid. Six different cases (listed in table 1) with one or two different control strategies (Single and Multi Master) are simulated to find out the sensitivity of frequency stability and voltage quality in these cases.

Table 1. Cases studied in this paper to find out the effects of certain changes in the system configuration.

Frequency reference	Single Master	Multi Master	No
1. Reference situation	x	x	x
2. Smaller filters and lower switching frequency	x	x	-
3. Higher Inertia constant of synchronous generator	x	x	-
4. Change of synchronous generators control method when islanded from reactive to voltage control	-	x	-
5. Changes in the modulation method of Master Unit (and in filter type/size) from PWM to a) hysteresis or b) SVM	x	x	-
6. Change in the modulation methods of all converters (and in filter size) from PWM to SVM	x	x	-

The next chapter of this paper discusses briefly about power system stability both in traditional case with rotating machines and in microgrid case with converter connected units. After that the studied system is introduced and the simulation results are reported and discussed. Conclusions are stated in the last section.

VOLTAGE AND FREQUENCY STABILITY

Traditional power systems with rotating machines

Large centralized synchronous generators are directly connected to the grid in traditional power systems, so that there is a coupling between the generator rotor speed, the system frequency, and the power balance in the system. The fundamental equation that governs the rotational dynamics of the synchronous generator is the swing equation [3], [4]:

$$\frac{2 \cdot H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_m - P_{\max} \cdot \sin\delta = P_a \quad \text{[pu]} \qquad (1)$$

or

$$\frac{H}{\pi \cdot f}\frac{d^2\delta}{dt^2} = P_m - \frac{|E'||V|}{X_{trans}} \cdot \sin\delta = P_a \quad \text{[pu]} \qquad (2)$$

where, ω_s is the synchronous speed in electrical units in rad/s, H is the inertia constant (the stored kinetic energy in MW at synchronous speed per machine rating in MVA), δ is the angular displacement of the rotor in rad, P_m is the shaft power input less rotational losses in pu, P_e is the electrical power crossing the air gap in pu, P_a is the accelerating power, f is frequency, X_{trans} includes machine reactance X'_d and line reactance X_e when connected to infinite bus through it, and E' and V are machine and infinite bus voltage values. It can be seen from equation (1), that any imbalance in active power ($P_m \neq P_e$) will result in non-zero accelerating power ($P_a \neq 0$), i.e. the rotor of the synchronous generators will either:

accelerate $\left(\frac{d^2\delta}{dt^2} > 0\right)$ or decelerate $\left(\frac{d^2\delta}{dt^2} < 0\right)$. [5]

The inertia (H) of the synchronous machines plays a significant role in maintaining the stability of the power system during an occurrence of a power imbalance. From equation (1) we can see that, when the value of P_e alters (and P_m remains constant), a higher inertia constant (H) of the synchronous generator, causes less acceleration or deceleration of the generator rotor. [5]

Microgrids with converter connected units in microgrid

In conventional power systems the system frequency is coupled with the rotor speed of the directly grid connected large synchronous generators and power unbalance can be seen as changed system frequency. However, in an islanded microgrid it is possible that all generation units are connected to grid via converters and there is no inertia of rotating masses to affect the frequency. In that case the frequency has to be created by a power electronic device so that at least one unit has the input from a phase locked loop (PLL) connected to a 50 Hz reference sine wave generator and thus it creates a frequency reference for the other generators to synchronize with. Therefore the frequency control in a stand-alone power system with converter based units is an open-loop system and steady state or transient changes do not affect the frequency [6]. The frequency is more of less fixed and power unbalance cannot be detected in the classical way. Power unbalance can be detected in this case from voltage changes.

Two control strategies are used in simulations to maintain the frequency and voltage stability in an islanded microgrid and they are defined in this paper as follows:

1. *Single Master Operation*: The master unit (battery converter) is operated in Uf-mode (Uf-mode means that the corresponding unit is responsible for the control of the microgrids voltage and follows the reference 50 Hz sine wave) and all the other converters are operated in PQ mode (PQ mode means that the unit has constant active and reactive power output).

2. *Multi Master Operation*: The master unit is operated in Uf-mode and all the other converters are operated in PQf-mode, which means that every unit in the microgrid follows the same 50 Hz reference sine wave.

The previous simulation studies [7], [8] have showed that in many cases the Single Master Operation mode is enough to maintain frequency balance in islanded converter based microgrid, but in some cases simulation results have shown that the Multi Master Operation mode is recommended in islanded microgrid to ensure the frequency stability. So the study about the frequency and voltage stability of islanded microgrid and their sensitivity to certain changes is needed.

STUDIED SYSTEM AND SIMULATION RESULTS

Studied Urban Cable LV Network Based Microgrid

The studied urban cable LV network is shown in Fig. 1. The system consists of one 800 kVA MV/LV-transformer which normally feeds LV feeders 1_1 and 1_2. The load in the microgrid consists of four passive loads on each feeder. The passive loads can be adjusted so that the loading of the transformer (which feeds LV feeders 1_1 and 1_2) gets some desired value between 0…150 % of the transformer ratings. Initially loading of the transformer was set to 15 % (123 kW) with power factor 0.985_{ind}. Cable parameters and R/X -ratio of the line used in the studied LV network (Fig. 1) are shown in table 2.

In following simulations the islanded microgrid is disconnected from main network with breaker so that microgrid will consist of feeders 1_1 and 1_2 (Fig. 1). In front-end of the feeder 1_1 there is a storage unit (battery 120 kW) equipped with converter 1 and L-filter (LCL-filter when hysteresis controlled). In feeder 1_1, further away from the transformer, there is also a PV cell (120 kW) equipped with converter 3 and L-filter. In front-end of the feeder 1_2 there is a synchronous generator (100 kVA) and further away from the transformer, there is also a fuel cell (120 kW) equipped with converter 2 and L-filter.

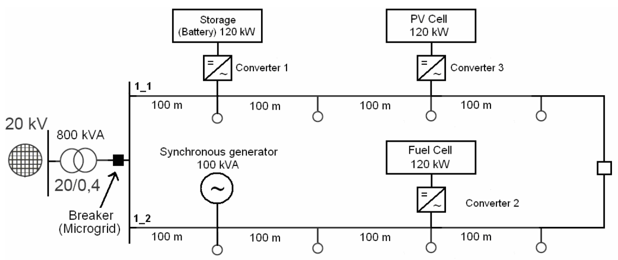

Figure 1. Studied urban LV network based microgrid.

Table 2. Resistance, Reactance and R/X ratio of LV network in Fig. 1.

	R (Ω/km)	X (Ω/km)	R/X
AXMK 4x185S	0.164	0.0817	2.01

Simulation Results

The results presented in following sections from these simulations show how different control strategies and modulation methods of converters (Pulse width, PWM, hysteresis and space vector modulation, SVM) affect to frequency, voltage total harmonic distortion and rotor speed of synchronous generator in islanded microgrid. Six different cases (Table 1) with one or two different control strategies (Single/Multi Master) are simulated to find out the sensitivity of frequency stability and voltage quality in these cases. Differences between six cases are shown in Table 3. Only the changes described in introduction (Table 1) are introduced in the system configuration between the simulation cases.

Table 3. Changes in system configuration in different simulation cases listed in table 1. (C1=Converter 1, C2=Converter 2 and C3=Converter 3)

	Filter type (size)	**Modulation method (switching frequency)**	**Inertia constant of SG** (MW/MVA)
1.	C1, C2, C3: L (2.25 mH)	C1, C2, C3: PWM (6 kHz)	0.105
2.	C1, C2, C3: L (1.02 mH)	C1, C2, C3: PWM (4 kHz)	0.105
3.	C1, C2, C3: L (2.25 mH)	C1, C2, C3: PWM (6 kHz)	0.42
4.	C1, C2, C3: L (2.25 mH)	C1, C2, C3: PWM (6 kHz)	0.105
5a	C1: LCL (L_1=0.1 mH, L_2=0.61 mH, C=6.9 µF) C2, C3: L (2.25 mH)	C1: Hysteresis (not constant) C2, C3: PWM (6 kHz)	0.105
5b	C1: L (2.25 mH) C2, C3: L (2.25 mH)	C1: SVM (6 kHz) C2, C3: PWM (6 kHz)	0.105
6.	C1, C2, C3: L (1.5 mH)	C1, C2, C3: SVM (6 kHz)	0.105

During each simulation run the timed events listed in table 4 are introduced.

Table 4. Timed events applied in each simulation run.

Time(s)	**Event/Change**
015	Converter 1 (Master Unit, Battery) is connected to network
0.5	Converter 3 (PV cell) and Converter 2 (Fuel cell) are connected to network (50 kW and 16 kVAr each)
0.34-	SG is connected to network (100 kW and 0 kVAr)
10	A) Islanding of microgrid B) Active power reference value for inverter 1 from PU-droop to keep voltage near 400 V C) Inputs for Phase Locked Loop (PLL) of converter 1 (single master mode) / all converters (multimaster mode) are changed to become from the 50 Hz 3-phase reference sine wave generator i.e. converters will now determine the synchronism and frequency of microgrid
20.0	Load increase through loading ratio of the transformer to 35 % (280 kW) with power factor 0.97_{ind}
30	Reconnection of an islanded microgrid
40	End of simulation

Frequency stability and voltage quality in different cases

Simulation results considering frequency and SG rotor speed stability in different cases are shown in tables 5 and 6 where stable cases are written in bold. Following abbreviations are used in Tables 5 and 6: S=Stable, US1=Stable before load increase in microgrid, US2=Continuous limited oscillations, US3=Unstable and DT=Damping transients after islanding and load change events. Simulation results about voltage quality (THD) of an islanded microgrid are presented in Table 7.

From the simulation results of Tables 5 and 6 it can be seen how the behavior of system frequency and the rotor speed of synchronous generator are linked in islanded microgrid. Stable operation of SG requires stable operation from the converter control in sudden changes such as load increase. Furthermore, stable operation of the converter in islanded microgrid depends on the control circuits of it (e.g. PI-controller parameters) ability to stay stable during sudden changes in much weaker grid (than normally) with more harmonic distortion in voltage. And added to that, the harmonic distortion under stable operation depends from the modulation method and switching frequency of the converter and also from the passive filter type and its sizing (Table 3). Higher inertia constant of SG in case 3 did not improve the stability in Single Master mode when compared to unstable reference case 1. But in case 3 with Multi Master mode higher inertia constant of SG damped down the transients when compared to stable reference case 1.

Table 5. Frequency stability of islanded microgrid in different cases (nominal 50 Hz). In brackets lowest / highest values (Hz).

	Single Master	**MultiMaster**	**No**
1.	US2 (49.5 / 51)	**S, DT (49.6 / 50.6)**	US3 (40/>100)
2.	US3 (40 / 55)	US1, US2 (49 / 51)	-
3.	US2 (49 / 51)	**S, DT (49.8 / 50.2)**	-
4.	-	US2 (48 / 54)	-
5a	**S, DT (49.7/50.4)**	**S, DT (49.7/50.4)**	-
5b	US1,US2 (49.7/50.3)	**S, DT (49.8/50.25)**	-
6.	**S, DT (49.9/50.15)**	**S, DT (49.85/50.2)**	-

Table 6. Rotor speed of synchronous generator in different cases (nominal 1 pu). In brackets lowest / highest values (pu).

	Single Master	**MultiMaster**	**No**
1.	US2 (0.98/1.04)	**S, DT (0.98 / 1.02)**	US3 (0.8/2.3)
2.	US3 (0.75/1.15)	US1,US2(0.96/1.04)	-
3.	US2 (0.96/1.04)	**S, DT (0.995/1.006)**	-
4.	-	US2 (0.96 / 1.05)	-
5a	**S,DT (0.99/1.015)**	**S,DT (0.99/1.015)**	-
5b	US1, US2 (0.999/1.008)	**S,DT (0.994/1.006)**	-
6.	**S,DT (0.998/1.002)**	**S,DT (0.996/1.006)**	-

Table 7. Voltage quality (THD) of islanded microgrid in different cases. (Lowest / highest values in %)

	Single Master	**MultiMaster**	**No**
1.	0.6 / 5	**0.85 / 2.5**	15 / >100
2.	2 / 30	0.7 / 4	-
3.	1.2 / 6	**0.85 / 2.5**	-
4.	-	1 / 22	-
5a	**1.2 / 1.4**	**1.2 / 1.3**	-
5b	0.75 / 1.6	**0.52 / 0.77**	-
6.	**0.21 / 0.22**	**0.16 / 0.17**	-

In Fig. 2 frequency behaviour in islanded microgrid with Multi Master mode in cases 1 and 2 is shown and it can be seen how in the case 2 with more harmonic distortion in the voltage (smaller filters and lower switching frequency) the control of converter 1 becomes unstable after load increase, which in turn leads to continuous limited oscillations.

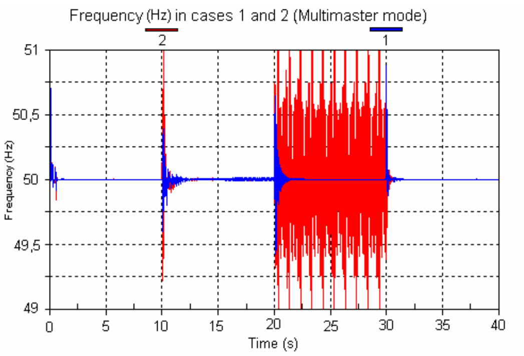

Figure 2. Frequency behaviour with Multi Master mode in cases 1 and 2.

The effect of different modulation methods, switching frequencies, filter sizes and operation modes (Single or Multi Master) on the voltage THD can be clearly seen from Fig. 3 where voltage THD behaviour in stable simulation cases with Multi Master mode is presented.

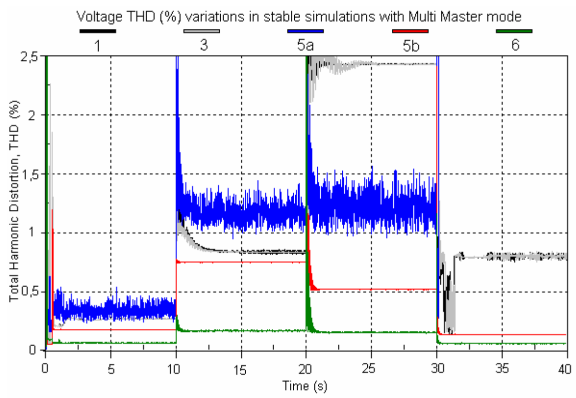

Figure 3. Voltage THD (%) variations during stable (table 5, 6, 7) simulations with Multi Master mode.

CONCLUSIONS

When studying the frequency stability of an islanded microgrid with converter connected DG units one have to be sure which stability problems are results from the converter controller instability, because in some cases highly distorted microgrid voltage led to converter control problems which in turn led to frequency stability problems in microgrid.
Based on simulations one can conclude that the Multi Master mode is not necessarily needed for frequency stability in an islanded microgrid, but it is recommended if the stability of the converter controller is not ensured. Simulations also showed how different converter modulation methods, switching frequencies and filter sizes affected to voltage quality (THD) and frequency stability. The converter with SVM modulation (case 6) was found to produce less voltage THD with smaller L-filter when compared to case 1 with PWM modulation. However, the control of it in the PSCAD model used needs still some further improvements, because it did not always acted as desired. Also use of an LCL-filter with SVM converter should be investigated to found out e.g, possible resonance problems between different LCL-filters of DG units in islanded microgrid.
Higher inertia constant of SG did not improve the stability in Single Master mode when compared to unstable reference case. On the other hand, when compared to stable reference case with Multi Master mode it damped down the transients. However, it is worth studying how large the share of DG units based on directly connected rotating machines could be connected in islanded grids to ensure stable operation after sudden changes / power imbalances.
The simulations showed that the microgrid voltage quality, i.e. converter modulation method, switching frequency and filter size, affects to frequency and also to voltage stability of an islanded microgrid. But from islanded microgrid stability point of view there is still considerable need to optimize these parameters and to improve the converter control behavior under different conditions and sudden changes in load.

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