Grid voltage control in islanded microgrids with inverter-interfaced power sources

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Abstract - The increased amount of distributed generation units connected to the distribution network has led to the development of the microgrid, which can operate in grid-connected or islanded mode. In the islanded microgrid, the mostly inverter-interfaced power sources are responsible for both voltage and power control. Therefore, adequate control algorithms for the microgrid inverters have to be developed. In this paper, an active power / grid voltage droop control strategy is applied for the power control. It is introduced as an outer control loop that determines the set-value of the inner grid voltage control loop. The grid voltage control is performed with different control strategies that are compared in steady-state and in worst-case circumstances. It is shown that the PI and fuzzy logic controller show the best overall performance in the microgrid application.

INTRODUCTION

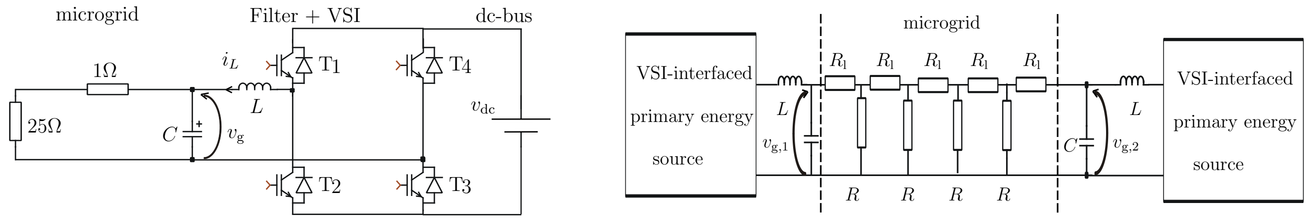
Because of recent technological developments, economical considerations and environmental issues, more and more power is generated by small-scale energy sources at the distribution level, which are called distributed generation (DG) units. Consequently, a major transition from the passive distribution networks with unidirectional power flow to active distribution networks with bidirectional flow is occurring. Together with the increasing amount of DG, this results in several technical implications and the present "fit-and-forget" strategy of connecting DG units needs to be changed. Therefore, a coordinated approach for integrating DG into the grid is required. For this purpose, the microgrid is introduced as a small-scale cluster of DG units, loads and storage elements at the distribution voltage level, mostly with voltage-source inverter (VSI) interface. From grid point of view, the main advantage of the microgrid is that it is treated as a controlled entity within the power system and it can be operated as a single load [1]. The microgrid has two operating conditions, namely the grid-connected mode and the islanded mode. In the grid-connected mode, the microgrid is connected to the grid at a single point of connection and it presents itself to the utility grid as a single entity. Also, it can work in a stand-alone, islanded operation mode in case of remote electrification or if the microgrid disconnects from the main grid during emergency situations such as voltage collapse.

In islanded microgrids, the DG units are responsible for both voltage control, power balancing and power sharing according to the ratings of the power sources. Therefore, in order to operate the islanded microgrid effectively, adequate control algorithms need to be developed for the VSIs of the DG units, which is the topic of this paper. The microgrid control is performed by means of two control loops in series: an outer power control loop and an inner grid voltage control loop.

The set-value of the grid voltage needs to be tracked strictly. Therefore, in this paper, the voltage of the grid is regulated with different control strategies that are compared in simulations by means of two main criteria: tracking performance and robustness. The set-value of the inner grid voltage control loop is defined by the outer power control loop. In this paper, an active power versus grid voltage amplitude droop control strategy is applied for the active power balancing and sharing. Other control strategies are possible, such as the distributed control method described in [2]. The reactive power control is out of the scope of this paper. Furthermore, the voltage profile along the microgrid line is studied for the case of a symmetric or asymmetric microgrid configuration with two equal or different power sources.

MICROGRID

For the grid voltage control, the microgrid is simplified as a single-phase load connected to a power source via a voltage-source inverter (VSI), Fig. 1(a). The VSI is connected to the microgrid through an LC filter for attenuation of the switching ripple. For the active power sharing and balancing, the more extended microgrid of Fig. 1(b) is considered.



(a) Grid voltage control (b) Active power control

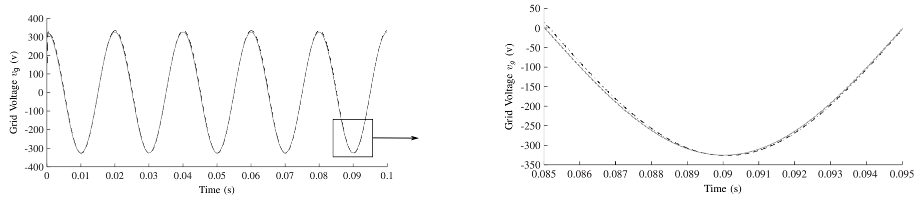
Figure 1: Microgrid configuration

VOLTAGE CONTROL

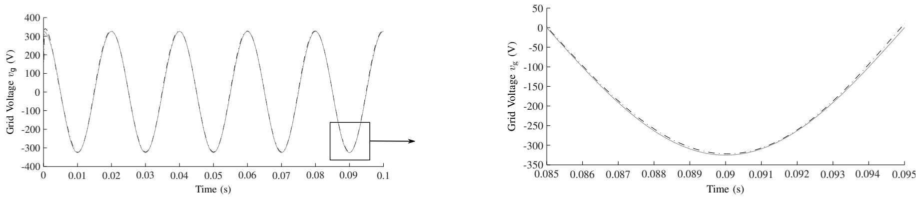
In this paper, three different control strategies for the grid voltage control are considered. First, the grid voltage is controlled by means of a discrete PID controller. The input of this controller equals the grid voltage error $v_{\mathrm{g}} - v_{\mathrm{g,ref}}$ and its output forms the input of the VSI. The second controller consists of two PI controllers in series, a relatively slow outer control loop and a fast inner current control loop, analogous to [3]. The outer PI controller forces v_{g} to $v_{\mathrm{g,ref}}$ and its output determines the input $i_{\mathrm{L,ref}}$ of the inner PI controller, which forms the switching signals of the VSI. This introduces more system knowledge than the PID control strategy as the inverter current i_{L} is measured. However, for both control strategies, an accurate system model is needed. Therefore, the third controller uses the fuzzy logic control technique, that does not require a system model.
The VSI filter parameters are: $L = 2$ mH and $C = 3$ μF and the dc-bus voltage equals 400 V. As, at first instance, only the grid voltage control loop is considered, the reference grid voltage is a predefined 50 Hz sinusoidal voltage with 230 V rms. In the next paragraph, this reference value will be determined by the outer power control loop.

Resistive Load

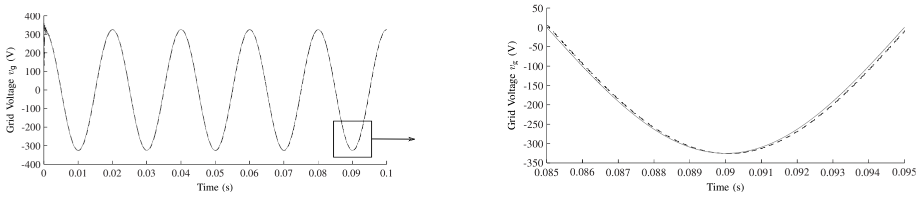
First, the tracking performance of the three controllers is compared. Therefore, the microgrid configuration of Fig. 1(a) is considered with load resistance $R = 25\ \Omega$ and line resistance $R_{\mathrm{l}} = 1\ \Omega$. The grid voltage tracking is shown in a time interval of 100 ms and also, a detailed figure of the desired versus the obtained grid voltage is depicted. All three controllers obtain a good overall tracking performance as shown in Fig. 2(a) for the PID controller, in Fig. 2(b) for the PI controller and in Fig. 2(c) for the fuzzy logic control strategy.



(a) PID controller



(b) PI controller

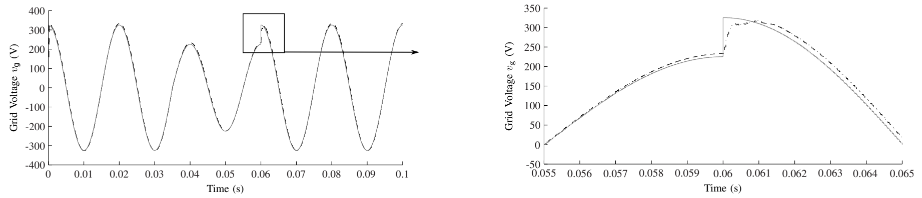


(c) Fuzzy Logic controller

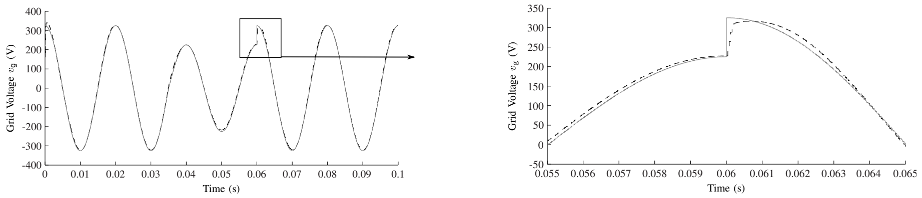
Figure 2: Grid voltage v_{g}(t): resistive load (— = Desired; ---- = Obtained)

Variable set-value

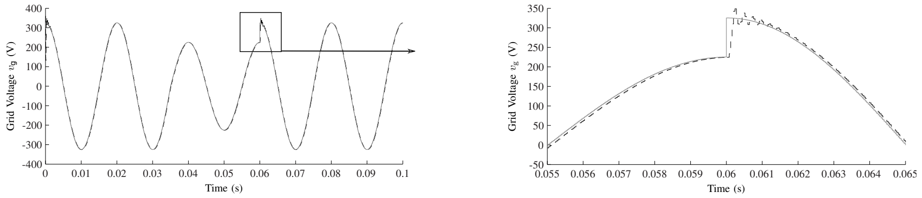
Secondly, a transient analysis is performed. Therefore, the grid voltage set-value changes with a higher amount than tolerable in microgrid applications, for the introduction of a worst-case scenario. The rms grid voltage changes from 230 V to 160 V at a time 0.035 s and increases again to 230 V at $t = 0.06$ s. The first transient occurs at a zero-crossing of the voltage, while the second one takes place at maximum voltage. From the simulations, it is shown that the voltage change at the zero-crossings causes a negligible transient phenomenon. For the case that the transient occurs at maximum voltage, the controllers give different performances. From Fig. 3(b), it is shown that the PI controller shows the best transient performance. The PID controller in Fig. 3(a) has a slightly higher tracking delay, while the fuzzy logic controller in Fig. 3(c) shows some small oscillation after the change of the voltage reference value.



(a) PID controller



(b) PI controller

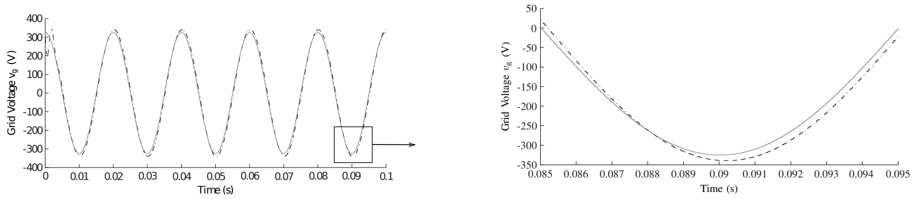


(c) Fuzzy Logic controller

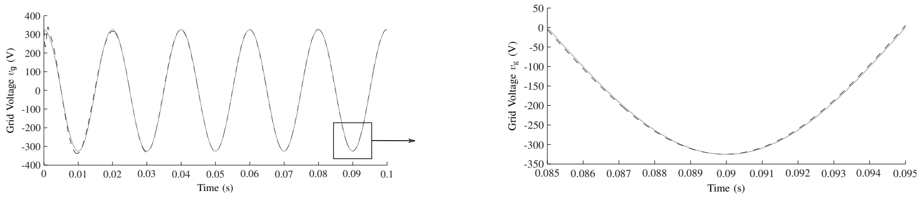
Figure 3: Grid voltage v_{g}(t): variable set value (— = Desired; ---- = Obtained)

Parameter sensitivity

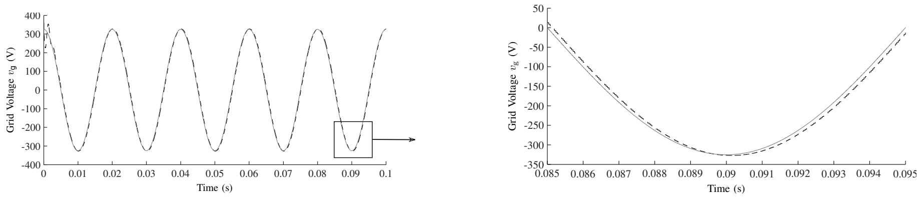
In this simulation, the robustness to parameter changes is studied. Therefore, the controllers are tuned with $L = 2$ mH and $C = 3$ μF, while in this simulation, the real filter parameters are: $L = 6$ mH and $C = 30$ μF. For studying a worst-case scenario, again, a very large parameter mismatch is implemented, larger than in practical applications. The PID controller in Fig. 4(a) shows the highest phase-lag and amplitude error, this is due to the lower system knowledge as compared with the PI controller. The PI controller in Fig. 4(b) shows a good overall tracking performance, despite the high parameter mistuning. As the fuzzy logic controller operates without the need for a model, it is little distorted by parameter variations. Therefore, the tracking performance remains good, as depicted Fig. 4(c).



(a) PID controller



(b) PI controller



(c) Fuzzy Logic controller

Figure 4: Grid voltage v_{g}(t): parameter sensitivity (— = Desired; ---- = Obtained)

An important advantage of fuzzy logic over the PI and PID controller is that there is no need for an accurate system model for the controller tuning. However, still some degree of system knowledge in advance is needed and mostly, this requires an iterative process of retuning the controller. The main advantages of the PI and PID controllers are that they are well-known and widely-used controllers that show good performance in a wide range of applications.

ACTIVE POWER CONTROL

For the active power sharing and balancing, two power sources are connected in parallel with multiple loads, following the configuration of Fig. 1(b). The power is controlled by means of the P/V droop control strategy of Fig. 5, that links the active power P with the grid voltage V_{g} in the mainly resistive microgrid. Therefore, the grid voltage V_g is determined by:

$$V_{\mathrm{g}} = V_{\mathrm{g,nom}} - m(P - P_{\mathrm{nom}}), \tag{1}$$

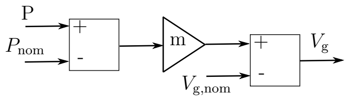
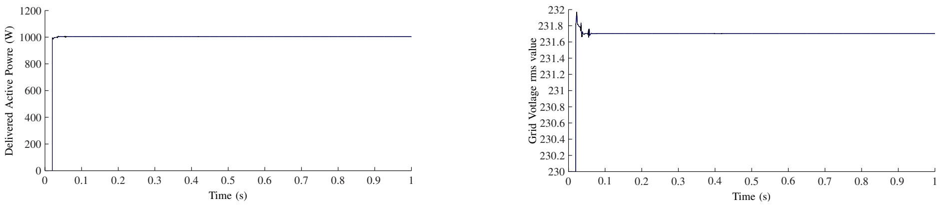


Figure 5: Droop control

with $V_{\mathrm{g,nom}}$ the nominal grid voltage, here 230 V rms, P_{nom} the nominal power rating and m the droop coefficient. In the following simulations, the grid voltage is tracked by means of the PI control strategy.

Power sources with equal generated power

In this simulation, the nominal active powers P_{nom} of the two sources are equal, namely: $P_{\mathrm{nom,1}} = P_{\mathrm{nom,2}} = 1125$ W. Also, the droop coefficient is equal ($m_1 = m_2 = \frac{1}{50}\frac{\mathrm{V}}{\mathrm{W}}$) and the microgrid configuration of Fig. 1(b) is symmetrical. From Fig. 6, it is concluded the inverters deliver the same amount of active power to the grid and have equal grid voltages. The power measurements are only valid after a fundamental period, hence, the 0 W initial power and the 230 V initial voltage. From the negative droop coefficient, it follows that the grid voltage is larger than the nominal voltage, because the delivered active power is less than the nominal power.



(a) Active power delivered to the microgrid

(b) Grid voltage rms value

Figure 6: Active power control, power sources with equal generated power: VSI 1 and VSI 2 show no difference in power and voltage profile (— = VSI 1; ---- = VSI 2)

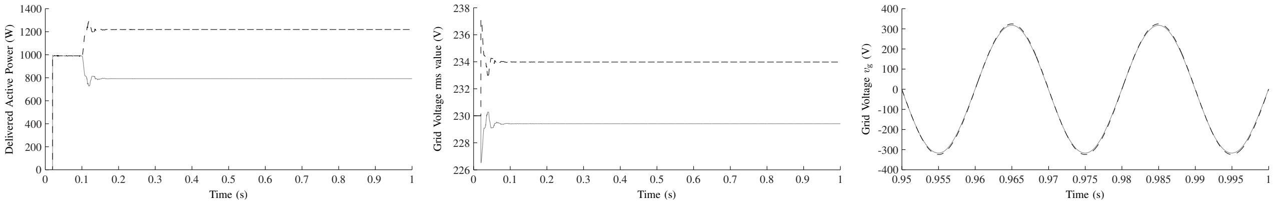
Power sources with different generated power

In this simulation, the nominal active powers P_{nom} of the two sources differ, namely: $P_{\mathrm{nom,1}} = 750$ W and $P_{\mathrm{nom,2}} = 1500$ W, while the droop coefficients remain equal. Fig. 7 shows that the delivered power of VSI 2 is less than its nominal value $P_{\mathrm{nom,2}}$ and therefore, its terminal voltage is larger than the nominal voltage and vice versa for VSI 1. Also, the inverter with the highest nominal power (VSI 2) delivers the largest amount of active power. Consequently, the power sharing can be influenced by setting the nominal power in the droop characteristic according to the power rating. The voltage tracking shows good performance in Fig. 7(c).

Voltage profile

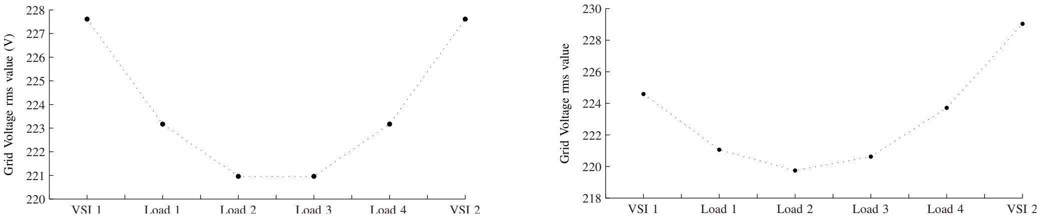
For the previous simulations, the steady-state rms voltage across the line is depicted in Fig. 8. For the case of the symmetric microgrid configuration of Fig. 1(b) and the VSIs with equal generated powers, the voltage profile is also symmetrical as is shown in Fig. 8(a). For the different power sources in the symmetric microgrid, the voltage near the largest power source increases as depicted in Fig. 8(b).

Furthermore, for an asymmetric microgrid configuration, two extra loads of 300 Ω are connected in parallel with VSI 2 via line resistances of 1 Ω. The power sources have the same power ratings as in Fig. 8(b), namely: $P_{\mathrm{nom,1}} = 750$ W and $P_{\mathrm{nom,2}} = 1500$ W. Fig. 9 shows the asymmetrical voltage profile along the line caused by these extra loads. The voltage near VSI 2 is decreased compared with Fig. 8(b) because of the extra loads connected to this power source. From this simulations, it is concluded that a typical voltage profile of a network with DG is obtained.



(a) Active power delivered to the microgrid (b) Grid voltage rms value (c) Detailed grid voltage v_{g}(t) of VSI 1

Figure 7: Active power control, power sources with different generated power(— = VSI 1; ---- = VSI 2)



(a) Equal inverters (b) Different inverters

Figure 8: Voltage profile over line: symmetric microgrid configuration

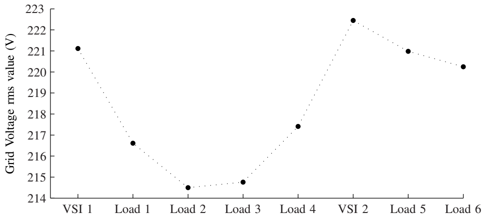


Figure 9: Voltage profile over line: asymmetric microgrid configuration

CONCLUSION

In an islanded microgrid, the power sources are responsible for both power and voltage control. In this paper, first, the voltage control of the microgrid is studied by comparing three control strategies. The tracking performance, transient response and parameter sensitivity of the controllers are studied. The PI control strategy shows a good overall performance, while being a conventional control strategy. Due to the lack of system knowledge compared with the PI controller, the PID controller shows more tracking error. The fuzzy logic control strategy shows good performance, even without the need for a system model.

Secondly, the P/V droop control strategy is implemented in the microgrid. A good power sharing and voltage control with high performance are obtained. Also, the voltage profile along the microgrid line is studied and it is shown that it is typical for a network with DG.

ACKNOWLEDGEMENTS

This work is financially supported by the FWO-Vlaanderen (Research Foundation - Flanders, Belgium). T. Vandoorn thanks the FWO for the Fellowship received. The research was carried out in the frame of the Inter-university Attraction Poles programme IAP-VI-021, funded by the Belgian Government.

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