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***Abstract*—This paper presents a novel control strategy to operate a low-voltage (LV) micro-grid in grid connected operation mode as well as autonomous operation mode. Depending on the inverter output impedance which is mainly resistive due to the LV cables a proper control strategy based on an unbalanced resistive droop approach is developed. The control strategy is verified by simulating fast changes of power production and simulating excess, shortage and average scenarios. Additionally, the control system can operate in an unbalanced network and can improve the active and reactive power distribution using a data communication system.**

***Index Terms*—Active and Reactive Power, Autonomous Operation, Data Communication System, Droop Control, LV Network, Micro-Grid, Output Impedance, Unbalanced Network**

I. Introduction

In the future, a transition in the low-voltage (LV) network might take place from the conventional design towards a micro-grid concept. The micro-grid is formed by small-scale distributed generators such as Micro Combined Heat and Power (μCHP), Photovoltaic (PV) systems and storage devices (flywheels, batteries and energy capacitors) close to the loads (households and shopping centers). The shift towards small-scale generation close to the loads can increase the reliability, efficiency and voltage quality of the grid on the condition that the network is adequately managed and coordinated [2], [7]. This is complex and is less predictable because the energy production of the distributed generators mainly depends on the weather conditions (solar, temperature and wind). Additionally, different stability problems can be caused by mismatching of supply and demand [6]. Moreover during disturbances (voltage drops, interruptions, faults etc.), the micro-grid must be able to operate in an autonomous operation mode, isolated from the upper-grid and complying with the voltage and frequency quality as described in the Dutch grid code [9]. In case of autonomous operation mode sufficient storage capacity must be provided.

The main objective of this research is to create an efficient and reliable control strategy to operate a micro-grid connected to the grid or as isolated island. This research fully concentrates on strategies based on inverter technology connected to a storage device.

Relevant side targets for the control strategy are:

1) The ability to maintain service under excess, shortage and average (demand) scenarios
2) The ability to react rapidly under fast energy production changes [3].
3) The ability to operate multiple inverters in parallel to manage and coordinate the micro-grid.

The research leads to a micro-grid simulation model based on an unbalanced droop controlled inverter including a communication interface between the inverters, implemented in DiGSILENT Powerfactory.

Section II provides a description of the analyzed micro-grid system and in section III the proposed control strategy is described. Simulation results illustrating the performance of the control strategy and the effects on the LV network are presented in section IV. Finally, section V gives conclusions and recommendations.

II. System Description

The analyzed micro-grid system consists of a combination of 3 storage devices including inverters and of 360 households with PV systems and μCHP systems as shown in fig. 1. The micro-grid can be connected to or disconnected from the upper-grid and transformer (10 kV/400 V, 630 kVA) by operating a breaker.

The houses are equally distributed among the 3 phases of 3 feeders (Al, 95mm^2, lengths of 400m, 450m and 500m). To simplify the simulations, the 40 houses connected to the same phase of a feeder are aggregated to 1 load and 1 generator (simulated as a negative load representing 40 μCHPs and 40 PV systems).

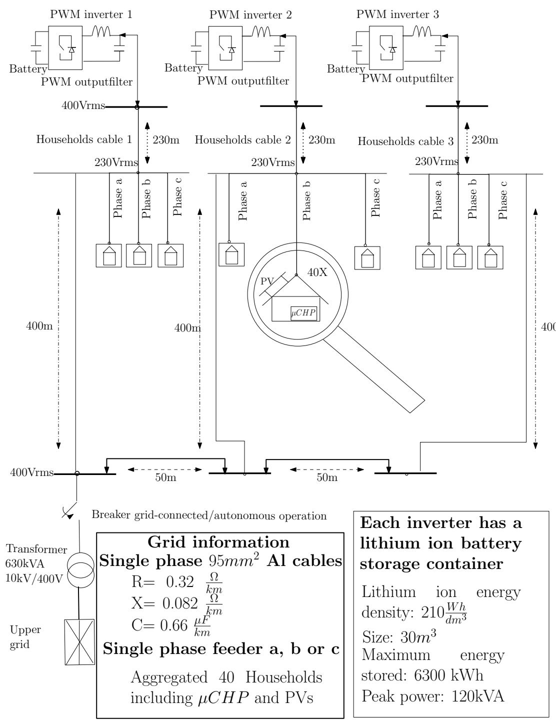


Fig. 1: Micro-grid system description

Loads (power demand of households), μCHPs (1 kW_e, 4 kW_{th}) and PV systems (1 kW_{peak}) are modeled based on load and generator power profiles from weather records (wind, solar and temperature data sets) acquired from [8].

The analysis is performed for the year 2020 considering an electrical power demand increase by 1.5% per year compared to the information provided by [8]. The storage systems are placed on each feeder (at distances of 630 m, 680 m and 730 m from the transformer). Lithium-ion battery storage is chosen because of the high performance and high energy density (210 $\frac{Wh}{dm^3}$) as described in [5]. A storage size of 6300 kWh (in combination with μCHPs and PV systems) is chosen to operate a minimum of 16 days in autonomous operation.

III. Proposed Control Strategy

The proposed voltage and frequency control strategy is based on unbalanced droop controlled inverters connected to a storage device. A communication interface (fig. 2) is developed to allow data exchange between the inverters for active (P) and reactive power (Q) set-points and to send requests to (de)activate allocated μCHPs for storage energy management purposes.

A. Voltage and Frequency Droop Control Strategy

Fig. 3 shows the block diagram of the proposed control strategy to operate the micro-grid in grid-connected and autonomous operation mode [2], [4], [7].

Depending on the control approach the battery storage system injects/consumes active and reactive power to control voltage and frequency. In case the inverter output voltage is below the nominal value, active or capacitive reactive power

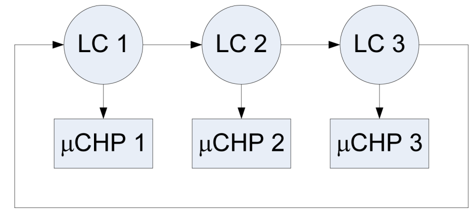


Fig. 2: Control strategy (LC=Local Controller, Battery storage system including inverter)

will be injected in the micro-grid. During over-voltage, active or capacitive reactive power will be consumed by the battery storage system. The inverter active and reactive power output is controlled by regulating the inverter output current.

At the end of the inverter output filter, the single phase voltages (U_a, U_b, U_c) and currents (I_a, I_b and I_c) are measured and separated into a real (d) and imaginary part (q). The phase locked loop (PLL) calculates the frequency f and phase ϕ using the real and imaginary voltage values. Then depending on the control approaches, P and Q are determined.

$$
\begin{aligned}
P &= P_0 - k_{pi}(f - f_0) \\
Q &= Q_0 - k_{qi}(U - U_0)
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
P &= P_0 - k_{pr}(U - U_0) \\
Q &= Q_0 + k_{qr}(f - f_0)
\end{aligned}
\tag{2}
$$

Equation (1) describes the inductive droop control [1] where k_{pi} is the proportional coefficient for active power and k_{qi} for reactive power. Resistive droop control (2) is described similarly as the inductive droop control, whereby the proportional coefficients are named as k_{pr} and k_{qr}.

The storage system injects only active and reactive power when the actual frequency and voltage deviates from the nominal voltage and frequency, therefore active and reactive power set-points, P_0 and Q_0 are set to zero.

Additionally, a dead band around the nominal voltage and frequency is implemented. The dead band prevents control during each small voltage and frequency deviation which can cause stability problems such as oscillations in the system.

Besides the stability issue, a dead band is placed to prevent the transformer tap changer switching continuously around the nominal voltage.

According to the Dutch grid code [9], the nominal voltage and nominal frequency are fixed at 230 V_{RMS} and 50 Hz.

The reference current values are determined by dividing the single phase P and Q reference values denoted by P_a, P_b, P_c, Q_a, Q_b and Q_c with U_{da}, U_{db} and U_{dc}. The current

[1] Droop approaches are named differently in several papers. In [1] it is denoted as conventional and opposite droop. In this paper inductive and resistive droop control is consistently used as it is more clear to name the approaches according to the output impedance at the power injection point (impedance of LV cables and inverter low pass filter).

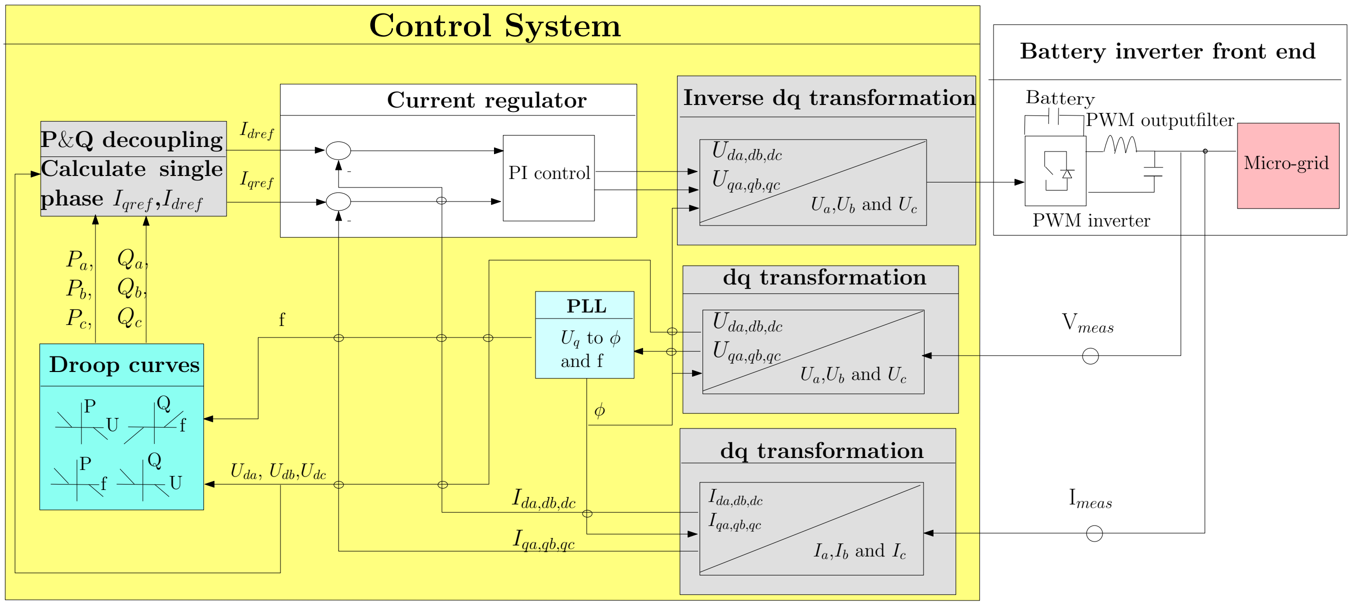


Fig. 3: Applied inverter control strategy including unbalanced droop control

regulator, a proportional-integrator controller forces the reference currents to be the output current by adjusting the output voltage U_a, U_b and U_c. By controlling each phase separately, an unbalanced droop control is created to handle unbalanced loading in the micro-grid.

B. Optimizing Active and Reactive Power Distribution

A data communication system is used to optimize the active and reactive power distribution. The battery storage system continuously receives active and reactive power reference values from the connected neighbor battery storage system. After receiving the average values (P_{comav} and Q_{comav}), the droop control recalculates the active (P_{ref}) and reactive power (Q_{ref}) reference values as described in 3 and 4. P_{ownref} and Q_{ownref} are the calculated active and reactive power reference values according to the local voltage and frequency measurements.

$$P_{ref} = \frac{P_{ownref} + P_{comav}}{2} \tag{3}$$

$$Q_{ref} = \frac{Q_{ownref} + Q_{comav}}{2} \tag{4}$$

C. Storage Energy Management

During critical shortage periods, it can happen that the battery is almost empty, therefore an emergency case enables the possibility of recharging the battery. The emergency case activates when the remaining battery energy is lower than a certain value even when the other battery storage systems are fully charged. The battery storage system sends an activation request to turn on a certain amount of μCHPs using the data communication link. Each battery storage system can only turn on the μCHPs located at its feeder (fig. 2).

IV. Simulation Results

A. Control Strategy Performance

The control strategy performance is verified for inductive and resistive droop control using the micro-grid shown in fig. 1. E.g. in July, due to the high temperature the μCHP is not producing any electricity and the active power production is fully supported by the PV system. Suddenly, a large cloud appears above the solar systems causing a fast decrease in active power production as shown in fig. 4. As a consequence of the sudden decrease in active power, the voltage level drops towards 210V as shown in fig. 5.

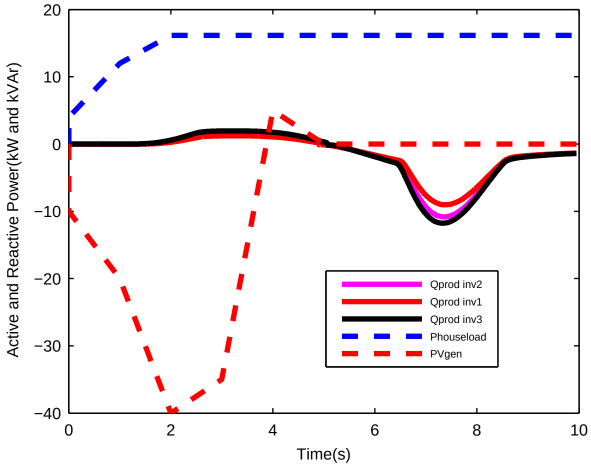
The inductive droop control strategy is tested using the load profile from fig. 4. Fig. 4a shows the reactive power produced by the battery storage system. Under influence of a change in voltage, capacitive (-) or inductive (+) reactive power is injected into the network. Due to the injected reactive power a decrease in voltage deviation is expected. However an overshoot is clearly visible in the voltage profile as illustrated in fig. 5a.

In case resistive droop control is applied on the previous example, active power is injected to correct the voltage deviations as illustrated in fig. 4b. Due to the active power injection, the voltage has improved in every part of the network and fig. 5b shows that the single phase voltage is equal everywhere in the micro-grid.

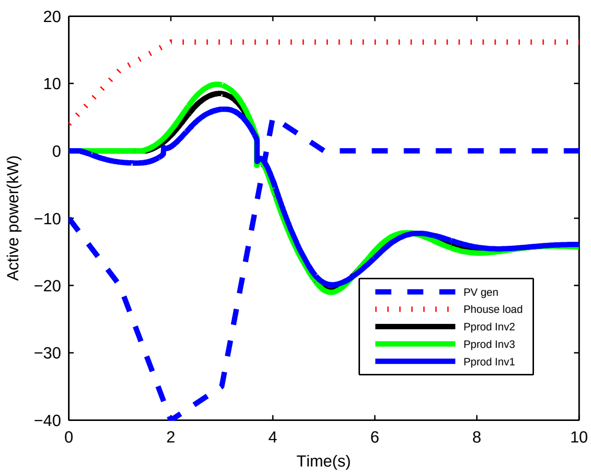
The resistive droop control has a more damped response compared to inductive droop control. In the remaining simulation results the resistive droop control strategy is applied.

B. Balanced Loading

In this section the simulation results for a week based on 15-minute-mean load and generator profiles during excess, shortage and average scenarios are illustrated [8]. The simulations results are illustrated using a box plot diagram (the box

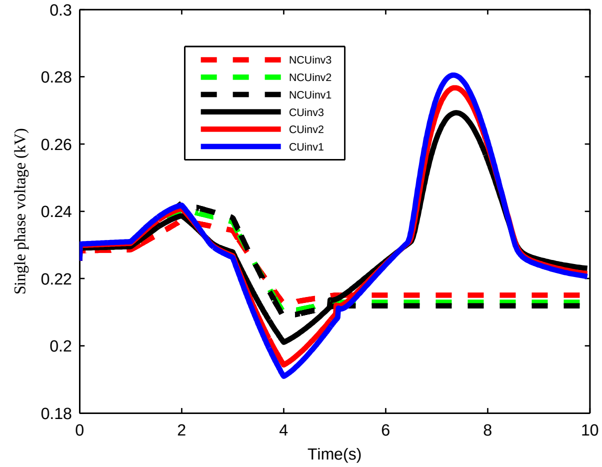


(a) Inductive droop control k_{qi}= 4.5 $\frac{kvar}{V}$

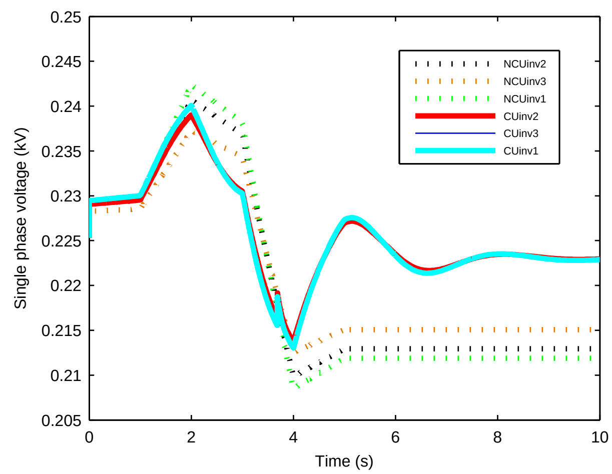


(b) Resistive droop control k_{pr}= 4.5 $\frac{kW}{V}$

Fig. 4: Generation and consumption power profiles



(a) Inductive droop control



(b) Resistive droop control

Fig. 5: Single phase voltage at the load (NC=Nocontrol, C=Control), reaction speed during fast changing weather circumstances

contains 50 % of the data and in addition minimum, maximum and median levels are shown) as described in [10].

Fig. 6 shows that due to the DG's penetration, the voltage level does not always comply with the standard as described in [9]. Especially, for the shortage scenario in January, excess scenario in July, average and shortage scenario in October. However, when the control strategy is enabled a clear improvement in voltage level is shown. The control strategy enables that shortage and excess periods are solved by injecting or consuming active power. Due to the control strategy, the allowed voltage range is not violated.

C. Autonomous Operation

Consider an example without active power production from DGs and only the storage devices inject active and reactive power into the grid. The active and reactive power demand varies during the 1200 seconds period (maximum and minimum power demand values: t=0s, 27.5 kW, 8.6 kvar; t=200s, 11 kW, 3.4 kvar; t=600s, 45kW, 14.1 kvar ; t=1000s, 11 kW, 3.4 kvar).

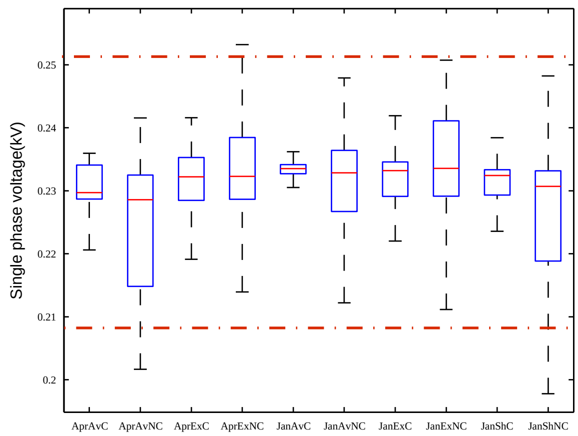
On the left side of fig. 7, the micro-grid disconnects from the upper-grid. The disconnection causes at the beginning an activation phenomenon for the voltage and frequency as shown in fig. 7a and fig. 7b. The frequency follows the reactive power demand and voltage is controlled by active power demand.

V. Conclusions and Recommendations

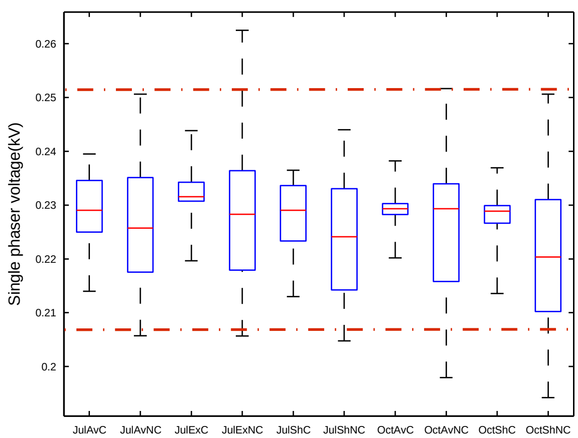
In this paper the control strategy based on resistive droop proves to be preferred to control voltage and frequency during grid-connected operation mode as well as autonomous operation mode in LV grid.

Additionally, a control strategy is developed to improve the voltage during excess, average and shortage scenarios.

A data communication system is developed to enhance a better active and reactive power distribution between battery

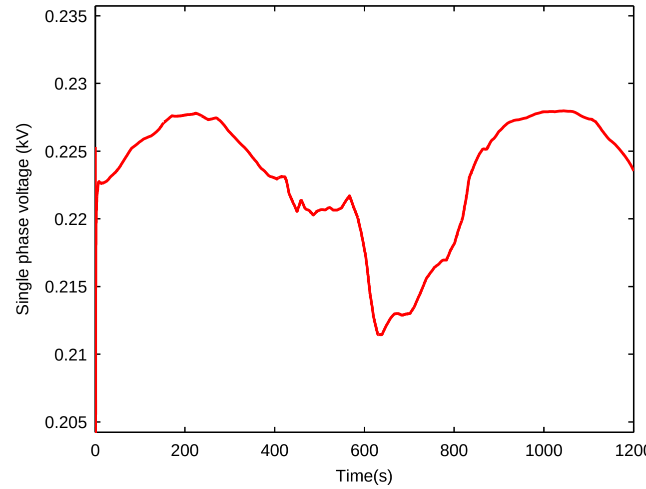


(a) Av=Average, Ex=Excess, Sh=Shortage, NC=Nocontrol and C=Control

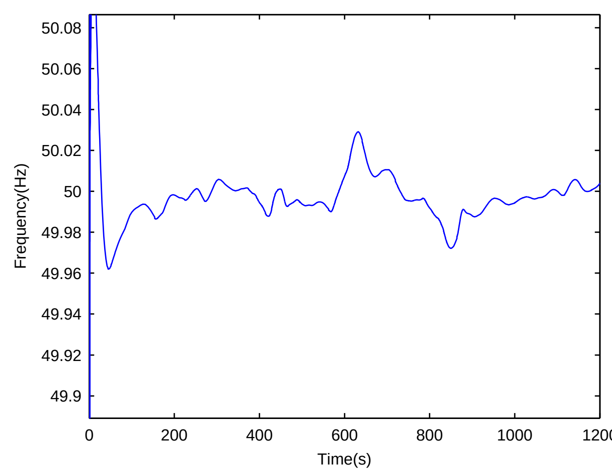


(b) Av=Average, Ex=Excess, Sh=Shortage, NC=Nocontrol and C=Control

Fig. 6: Voltage levels at the load throughout a week in Apr=April, Jan=January, Jul=July and Oct=October



(a) Single phase voltage(kV) at the load k_{pr}= 0.2 $\frac{V}{W}$



(b) Grid frequency controlled by k_{qr} = 0.000005 $\frac{Hz}{var}$

Fig. 7: Autonomous operation voltage and frequency

storage systems.

Research concerning the transition of grid-connected towards autonomous operation (transients) are still required.

A final aspect is to verify the simulation results by laboratory test.

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