DYNAMIC MODELLING APPROACH TO ASSESS CONTROL STRATEGIES OF DISTRIBUTED ENERGY RESOURCES

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ABSTRACT

Growing share of inverter-based power sources in distribution network brings new challenges to field of grid control, power management etc. This paper is focused on behavior of inverter-based power sources in loss-of-mains situation in low-voltage network. The transition to island operation should be one of the basic features of future smart grids. Focus of this paper is aimed on evaluation of P (f), Q (P,U) and P (U) control modes (introduced by EN 50549-1) performance in island operation. Fully equipped model created in PSCAD software is used as a tool to simulate variable scenarios and evaluate behavior of variable adjustment of control modes.

INTRODUCTION

Increasing penetration level of distributed energy resources (DER) brings many challenges in a wide range of possibilities of operating of these resources. There are a lot of features that DER needs to ensure. One of recent issue is behavior of inverter-based power sources in newly formed microgrid including inverter-based sources only. Crucial condition is loss-of-mains situation, which may be a condition for island operation initialization.

First part which needs to be addressed is the control and operation strategies of an inverter-based sources which can vary in depending on the structure of network, the modes of microgrid, the types of loads (demand character) etc. In current state of the art, there is no standard including operation and control strategies (control-loop topologies, setup, etc.) for inverter-based sources or microgrids. Ref. [1] and [2] summarize some control strategies which can be possibly adopted for P-Q and U-f control strategies.

European standard EN 50549-1 [3] aims to requirements for generating plants to be connected in parallel with distribution networks. However, this document does not consider some properties of inverter-based sources. Excluded from the scope are for example power system impact assessment e.g. assessment of effects on power quality, local voltage increase, impact on line protections operation, island operation of generating plants (both intentional and unintentional) etc. Anyway, neither EN 50549, nor distribution system operator’s (DSO’s) grid codes mostly do not mention any particular control system which should be implemented by manufacturers and operators of DERs. This fact offers large field of possibilities how to propose their control system/loops.

One of main features of future network could be to maintain in operation as long as possible to ensure continuity in power supply. In order to fulfill this requirement, some new features are applied and tested. Instead of disconnecting resources in a case of loss-of-mains by intended protections, there is possibility to operate network in an island mode. The issues of loss-of-mains passive, active and remote (communication-based) detection methods are described in [4]. Nevertheless, performance of the introduced P (f), Q (P,U) and P (U) control modes during island operation has to be considered.

CASE STUDIES DEFINITION

To define the issue dealt with in this article, it is necessary to take into account the possible states of the network. Due to increasing amount of photovoltaic (PV) installations in LV rural networks, there is possibility of existence only inverter-based power sources in eventual newly formed LV islanding or microgrid. Also, the microgrid may and may not contain battery system. Point-of-common-coupling (PCC) of LV microgrid can be MV/LV transformer (and it also can be a point of loss-of-mains detection). Crucial conditions in time of the transition to island operation are disponible and actual output power of sources, state-of-charge (SOC) of battery systems and direction of power flow through microgrid PCC. In situation of deficient LV network, there needs to be ability of sources to increase power output (if there is disponible power) or there need to be the accumulation system with ability to cover insufficient power in state of newly formed microgrid. In situation of surplus network, there needs to be ability to decrease power output of power sources or to start charging accumulation system.

However, in many cases of rural networks, there are no energy storage systems and power sources are delivering their maximum output power (i.e. there is no more disponible power). Under such conditions there needs to be a quick response of power management to keep operation of network in island mode after loss-of-mains situation. Demand response and presence of battery are not considered in this paper.

In general, islanding part of the supply system still have to fulfil requirements of EN 50160 std. [5], that defines supply voltage characteristics for a public LV network operation. As for a supply system on certain island, the mean value of fundamental frequency measured over 10 s shall be 50 Hz ±2 % (49 – 51 Hz) for 95 % of a week, and 50 Hz ±15 % (42.5 – 57.5 Hz) for 100 % of the time. Additionally, voltage magnitude variations of mean 10 minutes rms values shall remain in range U_n ±10 % for 95 % of a week and between -15 % and +10 % of U_n for 100 % of a week. However, the investigated cases are focused on the evaluation of successful transition to the island, therefore the application of those limits is not crucial.

In following, the studied cases are to be described.

Case 1

First case that can occur is a situation when sources have only ability to deliver active power without any consideration of other support. Loss-of-mains situation in this case will probably (but not necessarily) lead to change in frequency and voltage and then to corresponding protection trip.

Case 2

EN 50549-1 sets requirements for the connection of a generating plant to a LV distribution system. For inverter-based power sources, it defines necessity of active response to frequency deviation. Generating plants shall be capable of activating active power response to overfrequency at a programmable frequency threshold f_1 at least between and including 50.2 Hz and 52.0 Hz with a programmable droop in a range of at least s = 2 % to s = 12 % [3].

Second case that can occur is situation when inverter-based power sources in network works under condition of P (f) control mode.

Case 3

As addition to that, EN 50549-1 introduces support by reactive power. The general control modes are:

- Q setpoint mode – Q fix,
- Voltage related control mode – Q (U),
- cos φ setpoint mode – cos φ fix,
- Power related control mode – cos φ (P).

Those control modes are in fact Q (P) modes defining P-Q diagram of the power source, complemented by one Q (U) mode.

In order to avoid disconnection due to overvoltage protection, sources are allowed/forced to reduce active power output if necessary. EN 50549-1 allow to use P (U) control mode.

Third case can be considered as network with fully equipped inverter-based sources including P (f), Q (P,U) and P (U) control modes.

Case 4

Finally, **fourth case** can occur in network with source equipped by loss-of-mains indication, with ability to switch to master mode, i.e. a power source regulating island system voltage level and frequency exists. Practically, two states can occur – deficient and surplus network (micro-grid/ island). In considered network (with limited disponible power, without battery systems and without demand site management), there is possibility to keep operation only in surplus network. In case of surplus network, sources must decrease their power outputs to achieve power balance in microgrid.

NETWORK MODEL DESCRIPTION

Model of network components was created in PSCAD environment.

Power source model

Power source itself is modelled as a voltage source with inner impedance allowing its stable control.

Main feature of created power source model is selection of operation strategy. Each power source can be operated as master or slave (M/S) depending on the selected setting. In general, in synchronous operation all DER work as slaves – their P-Q control strategy is depended on required and disponible primary power and point of connection (PC) conditions. As addition to this, P (f), Q (P,U), Q (U) and P (U) control modes can be allowed and adjusted (within the limits of the EN 50549-1 requirements). For loss-of-mains situation – transition to island operation mode respectively – there is feature of one selected source to switch to master – to switch to U-f control strategy.

For purpose of fully functional model, P-Q control strategy presented in [6] was adopted. On this fundamental scheme, P (f), Q (P,U) and P (U) control modes were bonded. Main scheme of P-Q controller is shown in Figure 1.

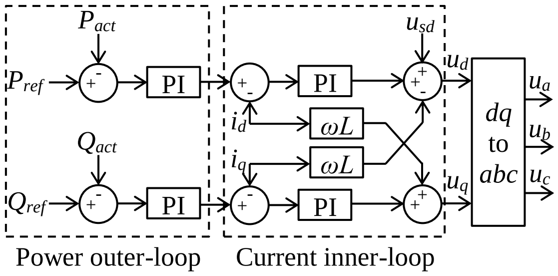


Figure 1 Schematic diagram of P-Q controller

For purpose of this paper, used setting of PI controllers parameters is shown in Table 1.

Table 1 PI controllers adjustment

Source	Control loop			
#1 #2 #3	Power outer-loop			
	PG_P 1)	ITC_P 2)	PG_Q	ITC_Q
	0.01	0.5	0.01	0.3
#1 #2 #3	Current inner-loop			
	PG_{id}	ITC_{id}	PG_{iq}	ITC_{iq}
	1	0.1	1	0.1
#1	Master loop			
	PG_u	ITC_u	PG_f	ITC_f
	0.1	0.5	0.1	0.5

1) PG – Proportional gain

2) ITC – Integral time constant (s)

P-Q diagram of power source is defined by selection of form of P-Q diagram shown in Figure 2 and by its proportion setup.

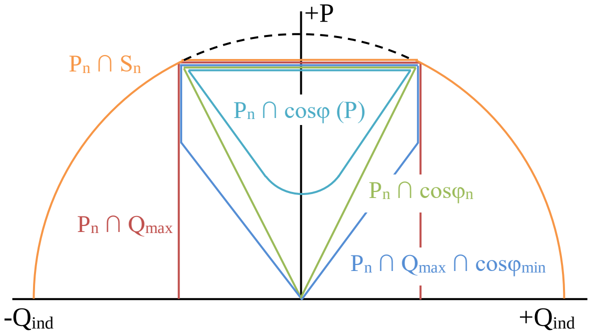


Figure 2 P-Q diagram variants

For purpose of this paper, widely used $P_n \cap \cos\varphi_n$ characteristic was chosen. In Table 2, used P_n and $\cos\varphi_n$, together with M/S setup of sources are listed. Master mode of source #1 was used only when fourth case was simulated.

Table 2 Nominal parameters and M/S setup of power sources

Source	P_n (kW)	$\cos\varphi_n$ (-)	Behavior in parallel operation	Behavior in island operation
#1	20	0.9¹⁾	S²⁾	S or M³⁾
#2	10	0.9	S	S
#3	15	0.9	S	S

¹⁾ chosen according to EN 50549-1
²⁾ Slave mode, ³⁾ Master mode

The active response to overfrequency (P (f)) setup of source is adjustable by using equation (1).

$$P_{req} = P_M + \frac{1}{s}\cdot\frac{(f_1 - f)}{f_n}\cdot P_M \,, \qquad (1)$$

where P_{req} is the required active power entering to control loop, P_M is the actual output power at the instant when the frequency reaches the threshold f_1, s (droop) is the ratio of the per-unit change in frequency (2 % to 12 %), f_1 is the frequency threshold (50.2 Hz to 52.0 Hz), f is the actual frequency and f_n is the nominal frequency (50 Hz). For source models, s = 5 % and f_1 = 50.2 Hz was chosen with regard to the recommended setting in the EN 50549-1.

The voltage related active power reduction (P (U)) setup of source is adjustable according the function shown in Figure 3.

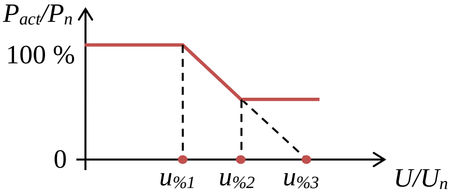


Figure 3 Function of voltage related active power reduction P(U)

Where P_{act} is the actually available power, P_n is the nominal power of source, U/U_n is the ratio of PC voltage and nominal voltage, $u_{\%1\text{-}3}$ are the voltage limits for active power regulation. According to [3] there is no recommendation for values of $u_{\%1\text{-}3}$ parameters, therefore $u_{\%1}$ = 109 %, $u_{\%2}$ = $u_{\%3}$ = 111 % were chosen to prevent increase of voltage over allowed limits. The dynamic response of the control corresponds to a first order filter having a time constant of 3 s.

Setup of Q (U) mode is adjustable according function shown in Figure 4.

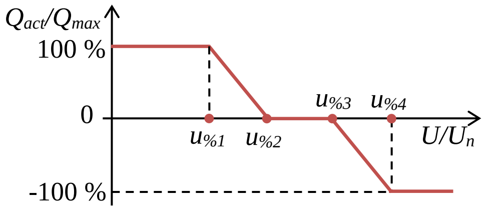


Figure 4 Function of voltage related control mode Q (U)

Where Q_{act} is the actual output reactive power, Q_{max} is the maximum allowed reactive power resulting from P-Q diagram, $u_{\%1\text{-}4}$ are the voltage limits for reactive power regulation based on PC voltage magnitude. According to [3] there is no recommendation for values of $u_{\%1\text{-}4}$ parameters, therefore $u_{\%1}$ = 94 %, $u_{\%2}$ = 99.5 %, $u_{\%3}$ = 100.5 % and $u_{\%4}$ = 108 % was chosen to test sensitivity and influence of its function. The dynamic of the control corresponds with a first order filter having a time constant of 3 s.

LV network

For the study of presented topic, part of real distribution network was chosen and modeled. Topology of the test network is shown in Figure 5.

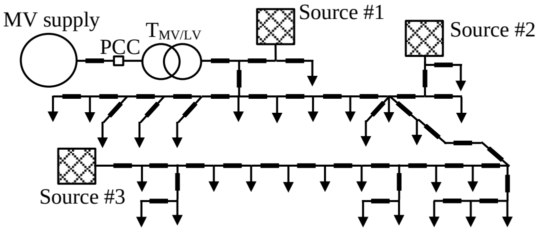


Figure 5 Topology of modeled LV network

The system is supplied from MV feeder, which is modeled as ideal three-phase symmetrical voltage source with source line impedance. Full model of 400 kVA distribution transformer in Dyn1 connection is used with nominal ratio of 22/0.4 kV. Line conductors of the LV distribution system are modeled using series impedances. Lengths of lines are from 25 m to 120 m. Loads are modeled as three-phase, star connected RLC segment with consumption from 0.5 % to 11 % of reference load power of 45.36 kVA.

SIMULATIONS AND EVALUATION

For presented study, some restrictions and simplifications are considered. Network is operated as three-phase symmetrical network. All three power sources have disponible their nominal power. Initial state is an equilibrium between power generated by power sources and sum of consumption together with network losses at the moment of loss-of-mains. This initial inner power of network is labelled as *eq.* ($S_{eq.}$, $P_{eq.}$, $Q_{eq.}$). Positive values mean lack of active power and inductive reactive power in the LV network. In opposite, negative values are related to surplus LV network. Also besides, loss-of-mains is initialized by breaker switch in PCC at preset time. In graphs, local parameters (PC voltage and output power) are presented for source #3 due to its location in the network (large line impedance means large sensitivity on changing parameters of network).

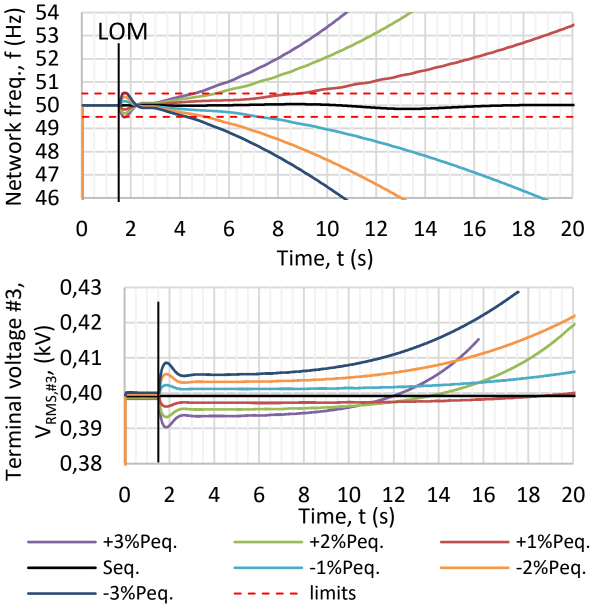


Figure 6 Simulation results – First case, P variations

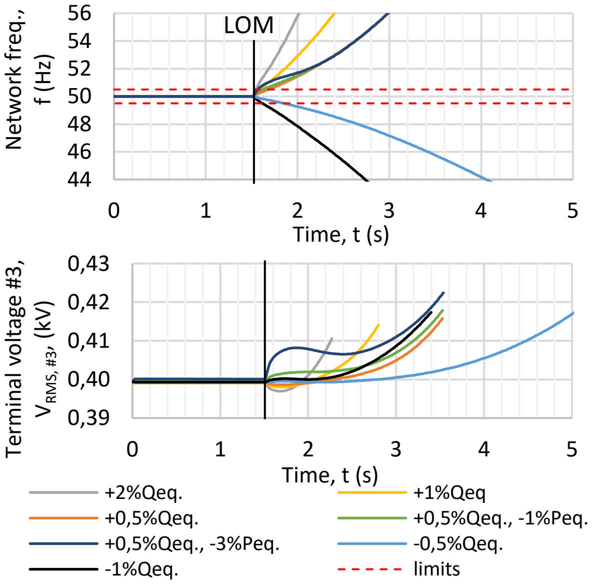


Figure 7 Simulation results – First case, P and Q variations

In the **first case**, sources generate maximum disponible active power only. Figure 6 shows deterioration in network frequency after loss-of-main situation in dependence on initial active power disbalance in newly formed island. Without any *V* and/or *f* regulation, the island is not able to establish a stable operation in case of initial disbalance. The bigger initial disbalance the faster way out of permissible limits can be observed. In case of reactive power disbalance, when loss-of-main occurs, the *f* deviation is even more significant (Figure 7). The resulting behavior of the circuit, from point of view of the system frequency, is due phase-lock-loop (PLL) in all slave sources. The demand to change of reactive power leads to phase shift of current phasor in view of voltage phasor, which in result leads to effort of voltage source to follow this shift. However, this shift cannot ever be reduced when source is to produce current in phase with terminal voltage only. The effort to follow the terminal voltage shift takes effect as change of voltage source frequency tracked by the PLL. Considering active power disbalance influence on frequency (Figure 6), the effect is in opposite to response of rotating generators.

In the **second case**, the P (f) control mode was activated. Comparison of simulations is presented in Figure 8. Rising tracked frequency by the sources leads evidently to reduction in set active power, due to P (f) control. It apparently suppresses rise in frequency (Figure 8 – upper), however accelerated energy disbalance (Figure 8 – middle) results in system voltage collapse (Figure 8 – bottom).

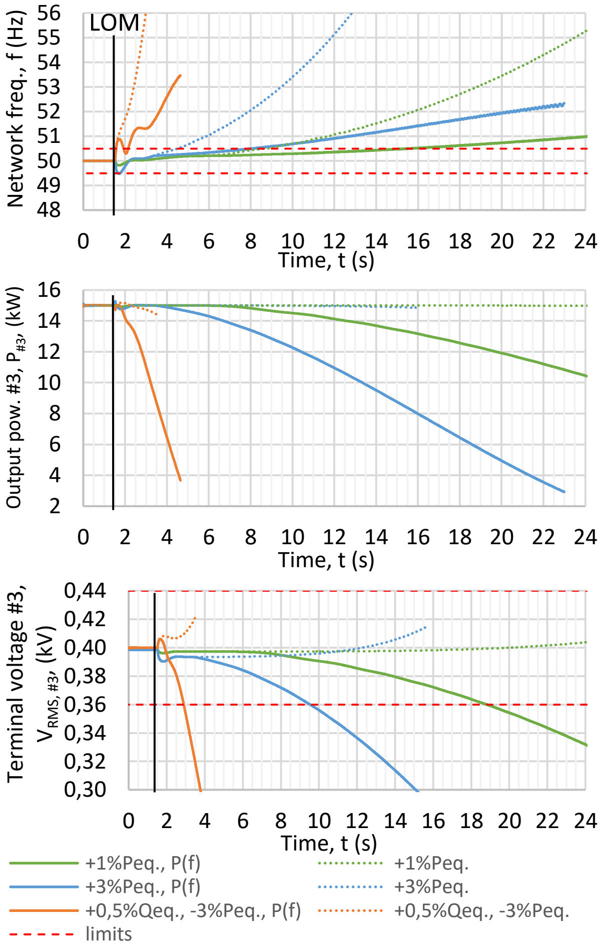


Figure 8 Simulation results – Second case in comparison with first case, P and Q variations

In the **third case**, Q (P,U) and P (U) regulation was activated in addition to P (f). Figure 9, in comparison to previous scenarios/cases, shows that under particular adjustment of the Q (U) characteristic the sources are equalizing reactive power with decreasing terminal voltage. Such support leads to delayed improvement of voltage magnitude across the LV system, nevertheless forced excess of reactive power extends voltage waves to which PLLs of the sources are locked. Therefore, tracked frequency is progressively decreased. P (U) mode is not contributing in this case.

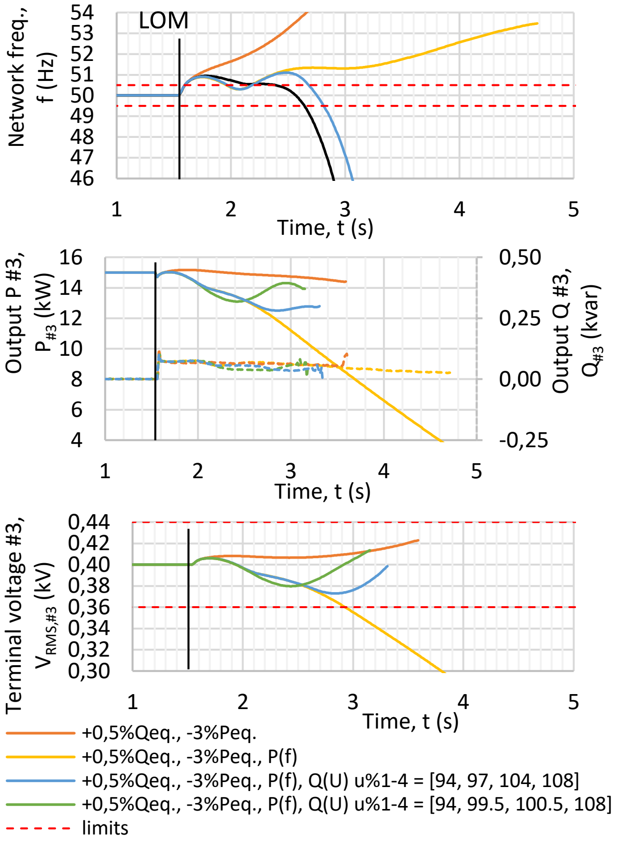
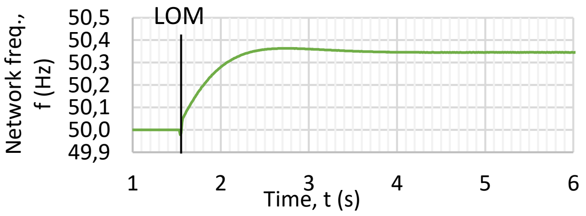


Figure 9 Simulation results – Third case, P and Q variations

As an example of the **fourth case**, surplus LV network, by means of power, was simulated. Master source is of ability to set the system frequency programmatically, by means of f (P), in order to control system active energy balance utilizing P (f) control modes of slave sources. The master f (P) statics is set to 2 %. While reactive energy is naturally covered by the master in full scale. Resulting response of the system in frequency can be seen on Figure 10 – upper. Under given conditions the system frequency is stabilized around 50.35 Hz. Considering slaves' P (f) threshold at 50.2 Hz, their active power is accordingly reduced, see Figure 10 – bottom. In the case of tested scenario, the resulting system voltage magnitudes, supported by Q (U) control mode of the slaves, are in acceptable range.



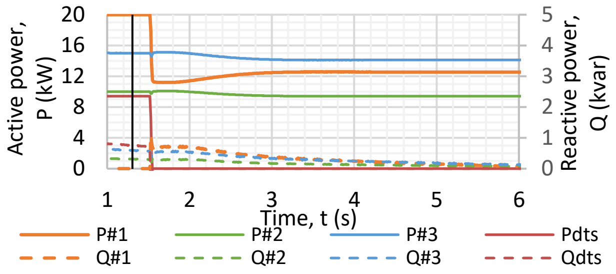


Figure 10 Simulation results – Fourth case, S to M transition

CONCLUSIONS

Software simulations offer many options how to study different setup, adjustment and functionalities of network components due to their complexity and interconnection. Presented simulations outline the issues of required regulation modes for inverter-based power sources: P (f), Q (P,U) and P (U) control modes. Presented cases and related simulations show some issues, which should be taken into account. Mentioned control modes can leads to stability of whole system - which been shown and described by fourth case's simulations. However, in case of absence of master control system in island operation, discussed control modes can lead to deterioration of system parameters due to their nature of function, which consequently affects other system parameters and components.

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