Part II of II

Technical Strategies for Voltage Power Regulation in LV Distribution Networks

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ABSTRACT

We report the integration of a novel voltage regulation strategy in the inverter control algorithm for Dispersed Generation (DG) applications. The adoption of a decentralized voltage control based on local curves allows the voltage profile to be controlled at the Point of Common Coupling (PCC) of the generators and, therefore, the capacity of existing distribution networks to host more generation from renewables. The work is focused on a low voltage distribution network and both the reactive power modulation and the real power curtailment are considered in the proposed local strategy. Both numerical and experimental analysis are necessary in order to test and validate the proposed voltage control strategy. Firstly, the performances of the proposed control are tested by a numeral analysis and the impact on both the electrical system and the inverter apparatus is evaluated. Secondly, the benefit of the control strategy is analysed by experimental analysis in a test facility to verify the feasibility of voltage regulation in a real feeder.

Experimental Application of a Multi-inverter Configuration— The numerical simulations previously described (in Part I of II of this article, *DG&AE Journal, Vol. 30, No.3*) aim to verify the performances of the proposed voltage control during a one-year period by exploiting a numerical model of a realistic LV distribution network.

In this section, the analysis of the voltage regulation is concluded by an experimental test exploiting a multi-inverter configuration. The aim of this analysis is to check the robustness and the performances of the voltage control laws in a test facility and to verify possible instability and reactive power fluctuations among DG units when several converters are regulating the voltage on the same feeder bars at the same time (i.e. in a multi-inverter configuration). The experimental application is focused on the transient behaviour of the system in a short time (tens of seconds). A set of experimental tests is carried out by exploiting a LV network model. The test set-up is depicted in Fig. 11.

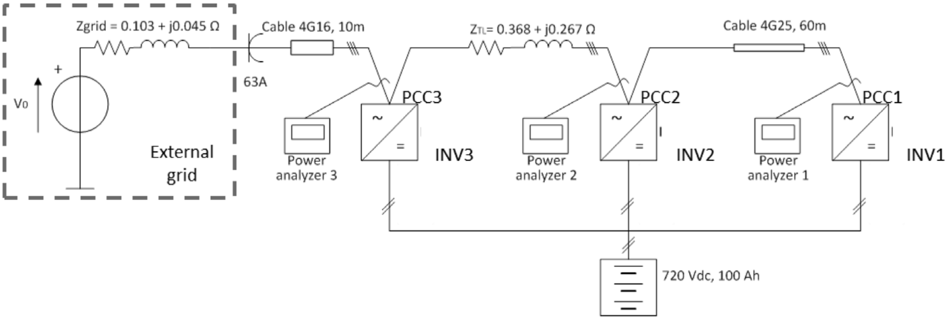

Fig. 11: Test set-up

The same LV test feeder adopted for the numerical analysis has been reproduced in the test facility. Three inverters for Photovoltaic (PV) application were adopted: in INV1 and INV2 (20 kW rated power) the four control laws of reactive power were set up; INV3 (30 KW rated power) is used as passive variable load. The inverters are fed by a battery pack of 720 Vdc rated voltage and 100 Ah capacity.

The connecting cables and impedances are defined in order to obtain, combining with the measured impedance parameters of the external grid (Z_{grid}), the same impedance value adopted in the numerical analysis Z_{TOT} = 0.59 + j0.32 Ω seen by the PCC of the inverter INV2 (PCC2 in the test set-up of Fig. 11). It allows a realistic network scenario to be reproduced. The following impedance values have been adopted:

- Z_{grid} = 0.103 + j0.045 Ω: impedance of the external grid,
- Cable 4G16: 10 m-16 mm^2 cable connected between the external grid and the PCC of INV3,
- Z_{TL} = 0.368 + j0.267 Ω: impedance connected between the PCC of INV3 and INV2.

Finally, a 60 m-16 mm^2 cable, named Cable 4G25, is used to connect the downstream inverter INV1 to the testing feeder.

The inverters adopted for the experimental tests are DC/AC three-phase single-stage converters connected to the feeder through a 270/400

V boost transformer (as shown in Fig. 5). A view of the set-up inverter system is shown in Fig. 12.

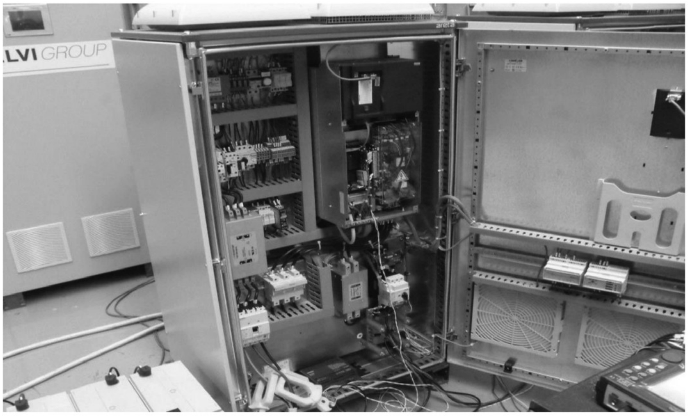

Fig. 12: Controlled inverter adopted in the test facility

In the test facility, the control software of INV1 and INV2 was changed in order to include the four control laws, as described in the section 0. The modified apparatus allow one to know the voltage, the reactive power and the real power at the PCC of INV1 and INV2 that are necessary for the reactive power modulation according to the control laws.

In the numerical analysis the annual capability of the LV feeder to host generation (annual multi-generator HC) and the global energy benefit (ΔE_{SS}) are evaluated for each of the control laws by exploiting a one-year chronological analysis. On the contrary, in the experimental test the behaviour of the controlled inverters INV1 and INV2 is evaluated in response to a pre-defined event. In this experimental simulation the dynamic behaviour of the control and its steady state response can be evaluated.

In the test facility various experimental settings were analysed for simulating the behaviour of the inverters under the different control laws. The test cases considered are reported in Table 8; the column “Controlled inverter” indicates the inverter in which the four local laws are set up, whilst the “Setting” column is the test setting considered for each case.

Table 8: Test cases of the experimental analysis

CASE	CONTROLLED INVERTER	SETTING
CASE A	INV2	Setting 1
CASE B	INV2	Setting 2
CASE C	INV1, INV2	Setting 3

The test settings are reported in Table 9; they include the events of real power injection simulated (from the "Initial condition" to the "Final condition"). These step events are used to generate the disturbances to the system (i.e. voltage variations for the activation of the Law A and Law B and a real power variations for the activation of the Law C and Law D) in order to study the dynamic behaviour of the local control strategies.

Setting 1 and setting 2 take into account step events of real power in order to evaluate a sudden regulation activation, on the contrary the setting 3 considers, for both INV1 and INV2, a ramp variation of the injected power, whilst the inverter INV3 is disconnected.

For example, in test case A the local control laws are set up only in the inverter INV2; the test setting adopted is Setting 1: INV1 initially absorbs 13 kW and then it is disconnected from the grid (P = 0), INV2 initially injects 18 kW and it does not change its production, whereas INV3 is disabled.

Test cases A and B consider only one regulated inverter (INV2), test case C considers the simultaneous control of INV1 and INV2, therefore the combined control effect of two inverters can be tested in order to evaluate the reactive power control loop stability of the two inverters.

The voltage oscillations measured at the PCC of INV2 by adopting each of the local control law during test Case B are shown in Fig. 13.

Considering the steady state, each law has a different impact on the voltage profile of the feeder. Table 10 reports the steady state values of inverter INV2. Voltage V is the voltage value reached in the steady state at the INV2 PCC, DV is the voltage deviation with respect to the unitary power factor operation condition V0 (DV = V0-V) and Q is the reactive power injected by the controlled inverters.

By looking at the reactive power involved (Q column) it can be stated that, for each case, Law C and Law D, in which the reactive modulation is computed as a function of the real power, absorb a higher amount of reactive power than the control laws directly linked to the voltage (i.e. Law A and Law B). As a consequence of the highest reactive power absorption the voltage deviation DV is the highest one.

In the numerical analysis the annual multi-generator HC was computed and the Law B has the highest HC improvement (highest ΔHC value, see Table 1); by the same analysis the highest global benefit ΔESS is reached by Law C (see Table 3). On the contrary, the experimental analysis is based on different assumptions; the DV index was exploited to evaluate the control law performances and Law D appears to be the most profitable

Table 9: Test settings – power injected by each inverter

		P INV1 [kW]	P INV2 [kW]	P INV3 [kW]
Setting 1	**Initial condition**	-13	18	Disabled
	Final condition	0	18	Disabled
Setting 2	**Initial condition**	-10	15	Disabled
	Final condition	0	15	Disabled
Setting 3	**Initial condition**	18	10	-15
	Final condition	13 (ramp)	15 (ramp)	0

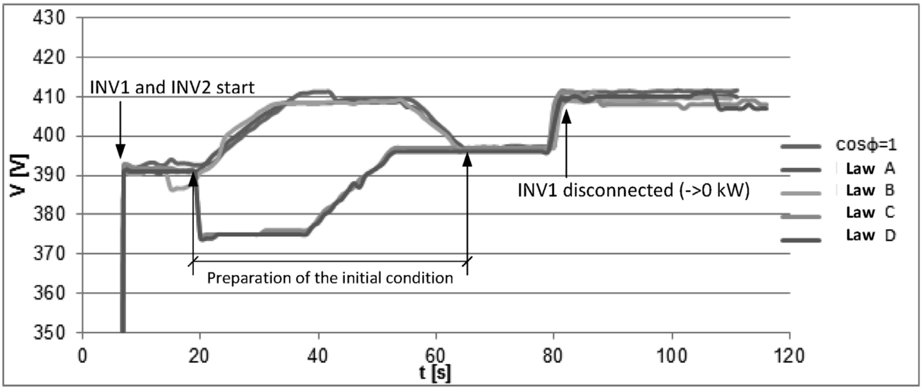

Fig. 13: PCC voltage oscillations of INV2 during the experimental test – Case B

Table 10: Steady state values of the inverter INV2 for each of the control law and test cases under analysis – experimental test

	CASE A – V0 = 415.4 V			CASE B – V0 = 411.6 V			CASE C – V0 = 431 V		
	V [V]	DV [V]	Q [kvar]	V [V]	DV [V]	Q [kvar]	V [V]	DV [V]	Q [kvar]
Law A	413.00	2.4	-5.75	409.89	1.71	-3.82	422	9	-9.63
Law B	413.00	2.4	-6.56	409.47	2.13	-4.92	421	10	-13.30
Law C	410.30	5.1	-9.22	407.86	3.74	-6.12	420	11	-12.30
Law D	410.20	5.2	-10.29	407.79	3.81	-8.50	417	14	-16.00

local control strategy.

An over-voltage in an LV feeder is reproduced in the test facility and the local control strategy set up in the inverters is able to modulate the reactive power and reduce the voltage profile within the admissible limits. For each test case, the dynamic behaviour of a multi-inverter control system does not create instability: the control set up in each inverter properly modulates the reactive power and a stable steady state operation condition is always reached. These local control strategies are suitable for setting up in real cases.

CONCLUSIONS

The paper is focused on the voltage control in the LV distribution system achieved by exploiting DG units as decentralized resources. Four local corrective control strategies have been proposed and discussed. The setting up of the proposed control in the inverter system requires an upgrade of both the hardware and software.

Numerical simulations were carried out in order to analyse the impact of the control on the voltage profile of radial feeders; the increasing in the HC index demonstrates the effectiveness of the proposed strategy. Nonetheless, a pure reactive power modulation is not completely resolving and in the case of high penetration of DG a real power curtailment is necessary to extinguish the over-voltages. Nevertheless, the reactive power modulation proves to be useful even combined with the real power curtailment; the combination of the two strategies allows the HC to be further improved with only a small real power cut.

Looking at the inverter, the increase in the inverter system losses is negligible and the upgrade costs are minimal, therefore the reactive power modulation is well justified by the improvement in the voltage quality.

Finally, a real inverter has been upgraded for reactive power regulation and it has tested in test facility by recreating a real operation condition of a LV feeder. In particular, real power events are exploited to cause voltage oscillations at the PCC of the inverters in order to evaluate the dynamic performances of the regulation and the steady state operation point. The experimental test depicts that the control strategy is effective without incurring in reactive power oscillations among the inverters.

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