ANALYSIS OF DYNAMIC PERFORMANCE OF DISPERSED GENERATION CONNECTED THROUGH INVERTER TO DISTRIBUTION NETWORKS

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INTRODUCTION

In recent years, Dispersed Generation have been broadly used and are expected to become in the future electric power system an important way for exploiting distributed energy resources or for supplying associate demands of electricity and heat (cogeneration).

DG are relatively small, usually in kW to MW range, are generally connected to the grid at substation, distribution feeder or customer loads at customer premises and many of them make use of new technologies which generate power in the form of Direct Current (Photovoltaic, Fuel cells, ...) or in the form of Alternate Current at a frequency different from the required 50 Hz (Wind generators, Microturbine,...). In these cases interface back-to-back voltage source converters are needed.

This paper describes the dynamic performance of distributed generators connected through inverters to distribution networks under abnormal operating conditions.

In addition, in the hypothesis of future distribution system configurations where portions of the network could be supplied either by the feeder or operated in islanded mode (microgrids), the case of DG units supplying local loads on a limited portion of the network has been considered.

By means of suitable interface models, a systematic analysis has been carried out on systems having different types of generation units (photovoltaic systems, fuel cells, microturbines) and operating with the two following configurations:

- *all DG units are paralleled to the utility grid where they inject the respective production;*
- *two or more DG units supplying an "intentional system island".*

For each configuration an appropriate control scheme is considered. Dynamic simulations has allowed to investigate the behaviour of the main electric parameters under perturbed conditions (load insertion or shedding, voltage sags) and faulted conditions.

Aim of the investigation is to verify, in the view of a growing diffusion of these new technologies, the needs of modify or install new network protection schemes in order to ensure reliable and safe operation. From the analysis, valuable results have been obtained, useful for assessing the impact of such devices on the quality of the supply and on the protection selectivity, also in comparison with the behaviour of a set of same rate synchronous DG units.

MODEL OF INVERTER INTERFACED DG SOURCES

For network study purposes an inverter interfaced DG source may be represented by a DC voltage source placed before the inverter.

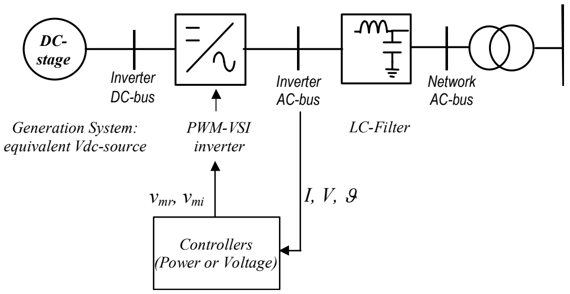

Fig. 1. Model of inverter interfaced generation system.

Fig.1 shows a block diagram of the model, whose main components are:

- a DC voltage source, representing the DC stage of a generic source system;
- a PWM-VSI inverter interfacing the DC system to the power frequency AC network;
- a low-pass LC filter which blocks the inverter generated high frequency harmonics and enables the inverter stand-alone operation modes (UPS) [1].

Assuming that the power demand is always within the capability of the device and the primary generator controls keeps the DC-bus voltage constant, the analysis can be limited to the inverter control, with no need of representing the more complex dynamic behaviour of the up-stream generation system [2, 3].

Inverter devices can be operated with different control schemes, depending upon the operation mode of the DG.

For a grid-connected inverter it is possible to adopt either an active and reactive power control scheme (namely PQ control) [2-5] or a control of active power and voltage (PV control) for reactive power compensation [6]. The former is the most commonly adopted control.

For stand-alone inverter a voltage/frequency control scheme is generally used. A block diagram of the PQ control scheme adopted in this analysis for grid-connected inverters is shown in fig. 2. As depicted in the figure, the PQ control performs a transformation of the inverter output current from the physical a-b-c reference frame to the stationary d-q reference frame. It is thus possible to exploit the correlation existing between active power and direct current component (id) and between reactive power and quadrature component (iq). The PQ control is easily achieved by regulating id and iq in order to meet the reference values id-ref and iq-ref (inverter current control).

Then, the voltage signals generated by the controller, vmd and vmq, are transformed into vmr and vmi (real and imaginary part of PWM-inverter voltage reference).

The current reference values are dynamically set on the basis of the prevailing network voltage and the user defined active-reactive power set-points. The output voltage waveform of grid-connected inverter is synchronized with the grid voltage.

The scheme in fig. 3 shows the block diagram of the adopted voltage and frequency control. A stand-alone inverter must supply the load with given values of voltage and frequency, and it must automatically modify the output active and reactive power depending on the loads demand. It is essentially an analogue control formed by two control loops: an outer voltage regulation loop and an inner current regulation loop.

The former is necessary since in stand-alone systems there is no ac side voltage available for reference, which must be produced by the inverter itself and fed back to control the inverter. The voltage error is used to drive P-I regulators which produces the current set-point (id-ref and iq-ref).

The control is performed on the direct and quadrature voltage components. Control of both voltage amplitude and frequency can thus be achieved.

When two or more DG units supply an islanded portion of the network, different control schemes may be adopted, i.e.:

- all units are voltage and frequency controlled;
- one unit is voltage and frequency controlled, thus being the reference voltage for the islanded network, while all the others may adopt either a PQ or PV controller.

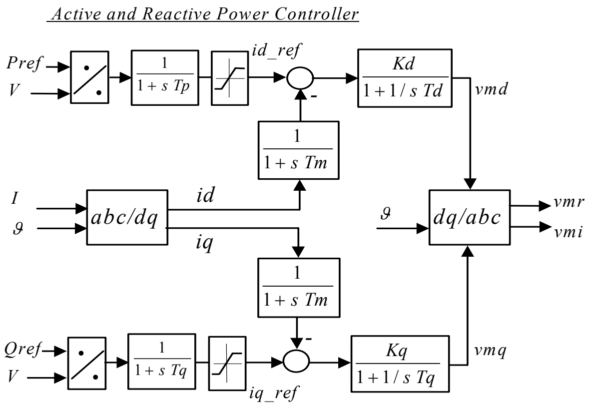

Fig. 2. P-Q Control Scheme

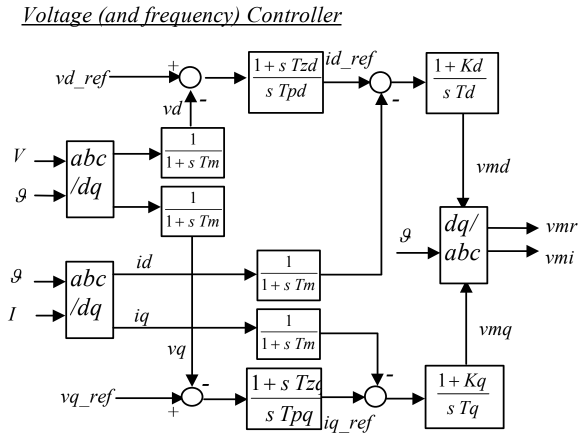

Fig. 3. V-f Control Scheme.

DYNAMIC ANALISIS

The dynamic behaviour of the main electric parameters of a distribution system with inverter interfaced DG units under perturbed or faulted network conditions have been investigated by means of dynamic simulations on a realistic case study network.

The above described control schemes have been tested on both grid-connected and islanded operation modes. Where applicable, the behaviour of static DG units are compared with that of similar size rotating generators.

The case study system is shown in Fig. 4. As depicted in the figure, it is made up by three feeders supplied by a common bus-bar at the HV/MV primary substation. Three DG units are connected to the network.

Data of interest for the dispersed generators, inverters and the feeders are reported in Table I.

Controllers modelling have been implemented and system simulations have been carried out using DigSilent, a commercial package for power system electromechanical and electromagnetic dynamic simulation.

A sample of the most significant results are reported in the following.

Grid Connected

Load change. In the event of network load variations, P-Q controlled inverters are only marginally involved in the usual dynamics of the network which results in small line voltage variations. After a short initial transient, the controller is able to restore and maintain the inverter output power to the corresponding set points.

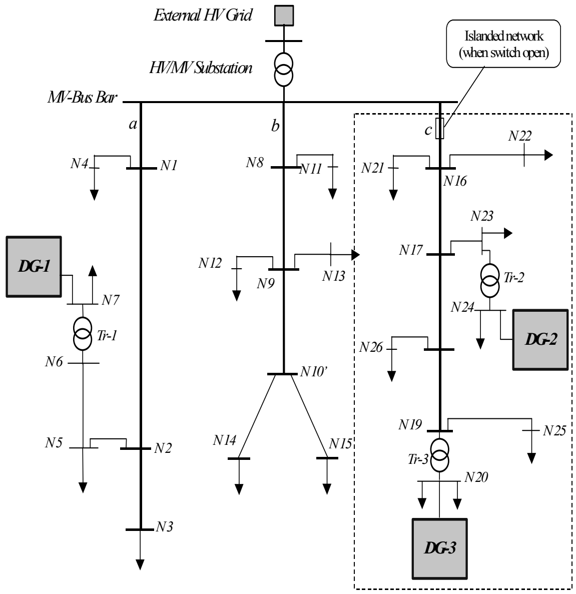

Fig. 4. Case study network

TABLE I - Main system data

Line	Lengh [Km]	GD	Grid-connected set-points		Island-operation set-points			
			P_{MW}	Q_{Mvar}	P_{MW}	Q_{Mvar}	$V_{p.u}$	f_{Hz}
a	22	*1*	0.4	0.15	-	-	-	-
b	28	*2*	0.2	0.10	1	0.15	-	-
c	22	3	0.4	0.15	-	-	1.05	50

Voltage sags. In the event of voltage sags, the inverters quickly react in order to restore the scheduled active and reactive power generated. The rate of increase of the inverter current is however limited by the relatively slow time response of the primary source. This can be seen in Fig. 5, reporting a comparison of the rms generator current behaviour in the event of a 0.5 p.u. voltage sag at the terminal of static DG unit and a similar size traditional rotating unit.

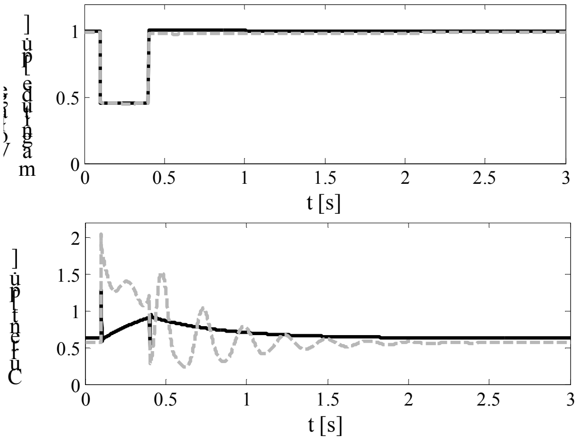

Fig. 5. Rms voltage and current at generator terminals during a sag event: inverters (solid line), synchronous generators (dashed line).

The voltage behavior in the two cases is almost identical since on P-Q controlled inverters and synchronous generators it's chiefly determined by the prevailing network voltage. On the other hand, the current transients are completely different: with slow and stable dynamics the power controller modifies the inverter current in order to maintain the active and reactive power output both during and after the voltage sag. Differently, the rotating generator is characterized by significantly high current transients and sustained oscillations. It is known that such perturbances may provoke nuisance tripping of synchronous generator protections as well as severe stress torque on rotor shaft [7, 8].

Symmetrical faults. In case of 3-phase short circuits located electrically near the GD, currents generated by inverter and rotating units have quite different behaviours. As shown in Fig. 6 (instantaneous values) and Fig.7 (rms values), in the event of 3-phase network short circuit, the inverter current is rapidly restored to the set value within 1 cycle, whereas the rotating generator current has the typical slow decay time thus giving a substantial contribution to the fault current.

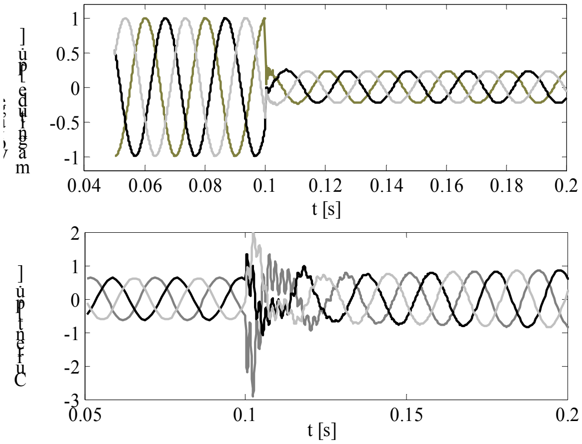

Fig. 6. Istantaneous values of voltage and current at inverter AC terminal during 3-phase network fault.

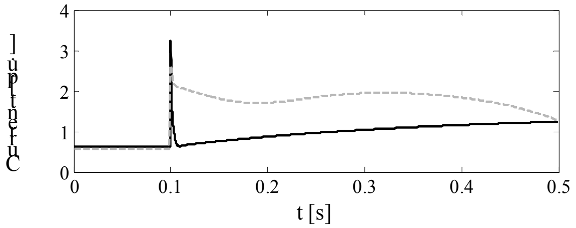

Fig. 7. Rms current at generator terminals during a 3 phase fault event: inverters (solid line), synchronous generators (dashed line).

Asymmetrical faults. Also in the event of network asymmetrical faults (single line-to-earth, line-to-line, etc.) inverter interfaced DG generates line currents smaller than those generated by a corresponding size rotating unit. As an example, fig. 8 compares the rms currents (unbalanced) injected by the two types of DG in the case of a network line-to-line fault.

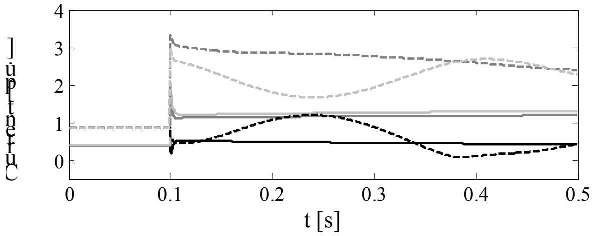

Fig. 8. 3-phase rms currents at generator terminals during a line-to-line fault event: inverters (solid line), synchronous generators (dashed line).

Island operation

Island operation using solely inverter fuel-cells or micro-turbines DG systems is critical since they have power conversion rates of the order of seconds which for many loads is too slow [9, 10]. A solution would be to add storage (either on the DC bus or the AC system) which means additional equipment and costs.

In network islanded mode of operation at least one of the DG units must perform Voltage and Frequency regulation (in such case a suitably sized storage should be included on the DC bus to insure fast response to any power change) while all other DG may be P-Q controlled.

The fast response of the V-f units may, in principle, ensure more stable AC voltages and a fast load tracking. This, however, means that the inverter must be suitably sized and have the required reservoir in order to be able to provide the necessary regulating power.

It can be seen that during the event all the regulating power is provided by the former unit, whose voltage is kept almost constant but the current increases considerably.

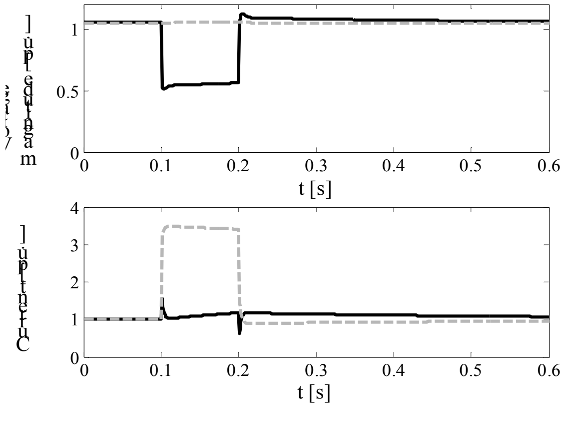

Fig. 9. Rms voltage and current at inverters terminals during a sag event in island operation: P-Q controlled inverter (solid line), V-f controlled inverter (dashed line).

Conversely, the current behavior of the P-Q controlled unit is similar to that reported in fig. 5 for the case of grid connected operation. In islanded operation mode, an effective power-sharing between the groups would improve system performance. This may be accomplished, for instance, by adopting a droop frequency control scheme such as that proposed in [2].

CONCLUSIONS

With reference to the new technologies of distributed generation, the dynamic behaviour of inverter interfaced DGs embedded on a distribution system has been studied in order to assess their influence on the system under perturbed conditions, in particular their contribution to the fault currents.

The dynamic performance of inverter interfaces, with different types of controller depending upon the operation modes, has been simulated on both a grid connected radial network and an intentionally islanded portion of the network (microgrid), comparing the results with the behaviour of corresponding size traditional rotating generators connected directly to the grid. From the analysis the following considerations can be drawn.

The typical problems arising from the connection of rotating generation units to the distribution network (namely increase of fault current levels and possible first swing instability of generators under severe perturbances) does not appear to exist in case of connection of P-Q controlled inverter interfaced GDs. In particular, the negligible contribution of these devices to the fault current levels allows to embed on the same network a considerable amount of generating units with no need of modifying or reinforcing the existing feeder protection schemes. The fast automatic reclosure of MV feeder breakers, which may give rise to dangerous rotor stresses on rotating generator shafts, does not appear so critical for inverter interfaced DGs.

However, in network islanded operation modes, where any load variation must be quickly tracked by the local generation and energy storage (such as the kinetic energy of the rotating groups) is determinant, the advantages of static units with respect to rotating generators are much reduced. In addition, the presence of V-f controlled inverter interfaces, necessary to perform the required voltage and frequency regulation in the islanded network, results in the injection of considerably high currents whenever such variables are perturbed. Such difficulties may be overcame with a suitable dispatching of the load between groups, which however requires the development of different control strategies and the implementation of communication systems for information exchange between interfaces. This topic deserves further investigation in order to fully exploit the potentiality of static DGs in view of future microgrid based distribution systems.

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