2[nd] International Conference on Electrical Systems Design & Technologies, Hammamet Tunisia, Nov. 8-10, 2008

Control of Distributed Generation Units in Stand-Alone Industrial Networks

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***Abstract*--This paper proposes and investigates a control strategy for operating an industrial distribution network when isolated from a main utility in order to improve continuity of electricity to its important loads. In that islanded mode the paper present a method for using inverter interfaced Distributed Generation (DG) units. The supervisory controller defines all Distributed Generation units' reference powers with consideration of system and unit normal rating in order to maintain reliable and high quality power to the important loads. Simulation results verify that the proposed control scheme is effective for stable working of the stand-alone industrial network with dynamic and variable loads.**

***Keywords*--Distributed Generation (DG), Industrial Networks, Load sharing, Stand-Alone Network, Supervisory Control**

1. INTRODUCTION

Over the last few years, a number of factors have led to an increased interest in distributed generation schemes for producing electrical energy. Reduction in gaseous emissions (mainly CO2), energy efficiency or rational use of energy, deregulation or competition energy, diversification of energy resources, availability of modular generating plant, easiness of finding sites for smaller generators, short construction time and lower capital costs for smaller plant, and generation sited closer to load which may reduce transmission costs are some reasons for increasing penetration of Distributed Generation units [1-5].

Major commercial and industrial users of electrical power pay demand charges to the utility. DG units could be used to reduce demand charges. In addition to saving in demand charges there are some industrial factory or commercial building that can't afford outage of power and so one suitable way of increasing power supply reliability could be to supply the most important loads by DG units during any outage of utility. Since most DG units must have a power electronics interface, they can all provide the quality of power and voltage support during disturbances [6].

The research works in the recent papers about DG focus on two applications: a stand-alone system and a grid-connection to the utility mains [4-8]. In a standalone ac power supply, several DG units independently supply the loads with electrical power during outage of main power supply. In a grid-connected mode each DG unit is interconnected in parallel to the utility, and provides power directly to ac mains in order to cover increased power required by the loads and decrease demand charges. Hence, after any outage of utility, it can be possible to supply important load with the installed DG units if the system technical issue considered.

Typical distribution network with DG supporting units can be islanded from main network in case of a fault or a scheduled disconnecting the main grid. In that case the DG units can be use for supplying energy to loads. In this situation coordination of the numerous generators for sharing the real and reactive power output and control the system frequency and voltage are the main problem that should be solved.

Load sharing and voltage and frequency control of a stand-alone network can be achieved in different ways that have been addressed in several literatures [5-10]. In [7-9] a concept has been developed and improved using reactive power/voltage and active power/frequency droops for the power control of the inverters. The droops are similar to those in utility grids. This method uses the grid quantities voltage and frequency for coordination of the components. As [9] showed this way have good results for controlling the power and voltage of each DG unit. The main advantage of this way is that it doesn't need fast communication system and it is suitable for distribution system with long distance between DG units. However the droop method need complex control system and frequency is not regulated and it is important for sensitive loads in industrial networks.

A system with a voltage source as master and additional controllable power sources is investigated and presented in [11]. This approach has simple control algorithm in components, high expenditure for busses and their cabling and instead it require a supervisory control.

The master-slave approach is suitable in industrial network where the distances are short and communication between all parts of system is almost available and applicable. Also the available supervisory control is responsible for the power distribution and knows the situation of loads and system at any specific time.

This paper is concerned with the control strategy for the parallel operation of distributed generation systems (DG) in an industrial network after islanding form main utility. In particular, the paper proposes a method to control power sharing between each DG unit and maintaining voltage profile.

The rest of paper is organized as follows. Section 2 describes industrial network under study configuration. Section 3 focuses on modeling and control of the inverter that use for connecting DG units to network. In section 4 structure and feature of proposed control strategy presented and simulation results and discussion on a typical simulation system described in section 5.

2. Study System Structure

A single line diagram of a low voltage cable type industrial distribution network that was used in this study for investigating proposed stand-alone network controlling scheme showed in Figure 1. The system consists of four feeders that supply from utility via a 20/0.4 KV transformer and data of all component of system can be found in appendix. The important part of system consists of 9 buses and 8 loads in 2 radial feeders.

When the utility is available two Distributed generation units (DG 1 and DG 2) produce some part of energy needed for the system in order to reduce demand charge. The system is considered to become islanded after a fault for the utility or a preplanned disconnecting from utility via turning the main switch off.

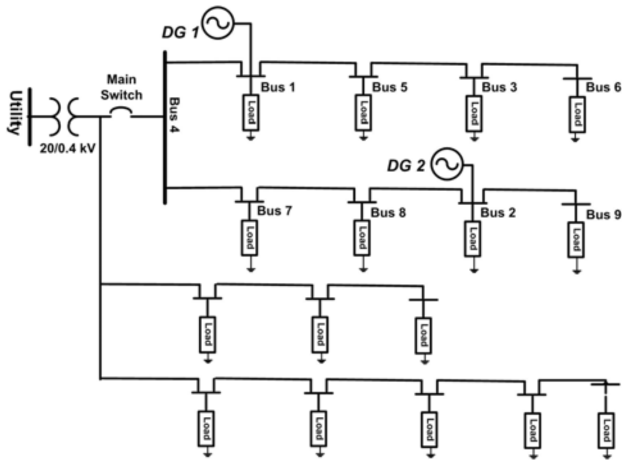

Figure 1: Single line diagram of the system under study

3. Modeling and Control of Inverter Interfaced DG Units

Basically each DG unit may have DC type or rectified generation unit (Fuel cell, solar cell, wind turbine, micro turbine…), storage devices, DC-DC converter, DC-AC inverter, filter, and transformer for connecting to loads or utility in order to exchange power [12-15]. Model and dynamic of each of this part may have influence in system operation. But here for simplification it is considered that DC side of the units has sufficient storage and considered as a constant DC source. Hence only DC-AC inverter modeling and control investigated in this paper.

A circuit model of a three-phase DC to AC inverter with LC output filter is further described in Figure 2. As shown in the figure, the system consists of a DC voltage source (V_{dc}), a three- phase PWM inverter, an output filter (L_f and C with considering parasitic resistance of filter- R_f). Sometimes a transformer may be used for stepping up the output voltage and hence L_f can be transformer inductance [16].

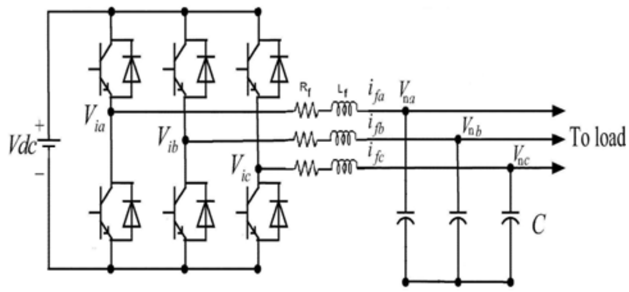

Figure 2: PWM inverter diagram

There are two ways for controlling an inverter in a distributed generation system [9-12]:

A. PQ Inverter Control

This type of control is adopted when the DG unit system is connected to an external grid or to an island of loads and more generators. In this situation, the variables controlled by the inverter are the active and reactive power injected into the grid, which have to follow the set-points P_{ref} and Q_{ref}, respectively. These set points can be chosen by the customer or by a central controller.

The PQ control of an inverter can be performed using a current control technique in qd reference frame which the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power [17].

With the aim of Park transform and equations between inverter input and output [17], the inverter controller block diagram for supplying reference value of P_{ref} and Q_{ref} is as figure 3. For the current controller, two Proportional-Integral (PI) regulators have been chosen in order to meet the requirements of stability of the system and to make the steady state error be zero. With this control scheme, it is possible to control the inverter in such way that injects reference value of P_{ref}, Q_{ref} into other part of stand-alone network.

When the output voltage is needed to be regulated, the PV control scheme that is similar to PQ mode with feedback of voltage used to adjust Q_{ref}.

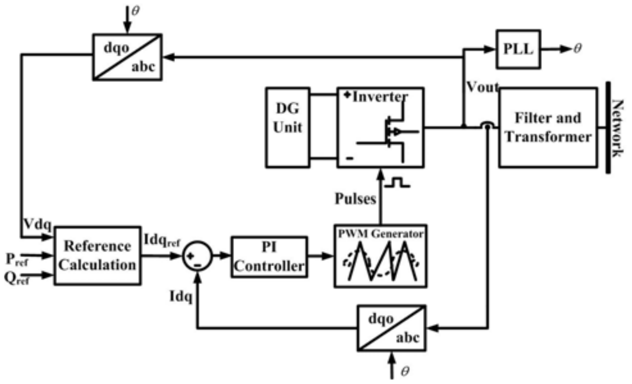

Figure 3: PQ control scheme of inverter

B. Vf Inverter Control

This controller has to act on the inverter whenever the system is in stand-alone mode of operation. In fact in this case it must regulate the voltage value at a reference bus bar and the frequency of the whole grid. A regulators work in order to keep the measured voltages upon the set-points. Moreover the frequency is imposed through the modulating signals of the inverter PWM control by mean of an oscillator. A simple PI controller can regulate bus voltage in reference value with getting feedback of real bus voltage. Figure 4 outlines this control strategy. In this case it is obvious that the DG unit should have storage device in order to regulate the power and voltage.

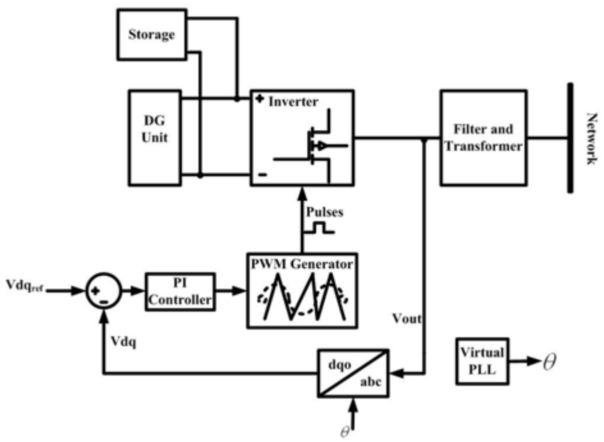

Figure 4: Vf control scheme of inverter

4. INDUSTRIAL STAND-ALONE SYSTEM CONTROLLER

If a group of DG unit is operated within a distribution system and the main power supply is connected, all the inverters can operate in the PQ mode because a voltage and frequency reference is available. In this case the DG units are expected to supply pre-specified power to minimize power import from the grid (peak shaving). In this grid-connected mode, similar to a conventional utility system, each DG unit can be controlled to generate pre-specified real and reactive power components (PQ-bus) or generate pre-specified real power and regulate its terminal voltage (PV-bus). The utility grid is expected to support the difference in real and reactive power requirements and maintain the frequency [17, 18] like slack bus generator in traditional system.

However when the utility is lost and network become islanded, the whole system must be shut down and all DG units must be disconnected because of lack of frequency support. If there are some important loads that should be supplied all time then it is important to find a solution to supply them and guarantee continuity of electricity supply.

In this case one of DG units must act as voltage reference and then it will be possible to obtain an exact balance between load and generation. That unit called Master DG unit and with duty of providing the reference voltage and frequency. The other DG units can work in PQ or PV mode and they don't expect to have contribution in transients change in loads and may be they used for long term load balance.

Such a Master DG unit should be coupled with a storage device with a large capacity in order to be able to compensate natural load and production variations.

The whole system must be centrally controlled and managed by a Central Controller that can be installed at the substation. The main criteria that should be met by the system Central Controller are as follows:

- Identify outage of utility and disconnect unimportant load and then changing control scheme of all DG units to stand-alone mode of operation with one master unit and other as PQ or PV mode.
- Maintaining stability and restoration of the system during and after load change or transients.
- Load sharing among DG units with consideration limits of each DG unit, including type of the DG unit, cost of generation, maintenance period, and environmental impacts.
- Maintaining the power quality and voltage profile in standard values
- Preparing Island network to reconnect to utility after reconnection of utility and Changing the control scheme of all DG unit to grid-connected mode.

These goals should perform by suitable controller. Two level of controller is suggested for this purpose:

A. **Local Controller**: At the first level inverter current is controlled according to desired active and reactive powers and with consideration of inverter and switch ratings. This controller scheme has been described in section 3.

B. **Supervisory Controller**: This level of controller defines reference value of active and reactive of each inverter. Also this controller defines state of controllable loads if exist. The controller manages network operation by providing set-points to both loads and generation units. Commands are at format of power and voltage references for DG units and load shedding for controllable loads.

Since in this study a stand-alone industrial network considered, it is obvious that load profile is known and DG unit variable can be measured and transmit to supervisory control with existing communication facility in the network. So the supervisory controller have situation of system all time and can decide the proper load sharing and can control the system effectively. In this paper only operation and control of system during stand-alone mode investigated and controlling and recognizing transition between grid-connected and stand-alone mode and reconnecting to grid is out of this paper study.

5. SIMULATION RESULTS

To validate the effectiveness of the proposed control strategies in the stand-alone AC power system, a simulation test bed using Matlab/Simpower Toolbox is constructed for an AC 220 V (Ln)/50 Hz system that its single line diagram showed in figure 1.

It is considered that DG 1 is Master DG Unit and it act like a synchronous generator for producing voltage and frequency reference because it have storage device to overcome load change rapidly. The other unit, DG 2, synchronizes itself with the main unit via PLL and work at PQ mode of operation and its active power can change with command of central controller. In this study it is considered that DG 2 injects constant reactive power value of 40 kVAR. In fact this unit is responsible only for active power.

The whole system is simulated under some changes and various condition and the simulation results of system showed in figures 5 to 11. Initially it is considered that power references of DG 2 are set to 150 kW and 40 kVAR respectively. It can be seen from figures 5 and 6 that in this case the controller adjusted output power of DG 2 in desired value and as expected remaining needed power supply by Master unit DG 1.

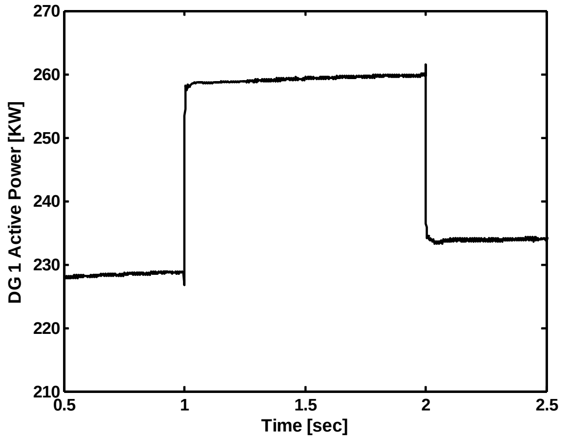

Figure 5: DG1 output power when load increase

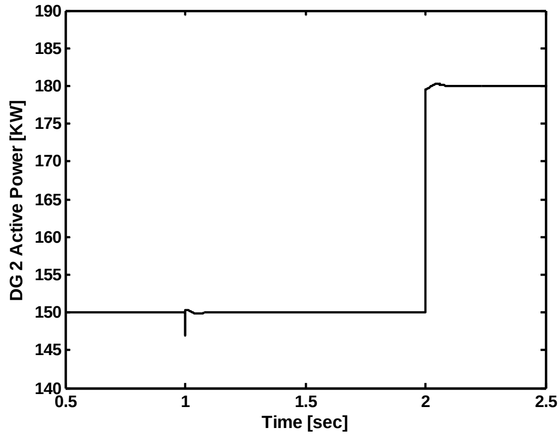

Figure 6: DG 2 output power when load increase

At t=1 sec load in bus 9 increased about 100% and it can be seen from figure 5 and 6 that the increased power supplied by master unit DG 1 and DG 2 work in constant power at predefined reference value. The amount of increased load supplied by master unit as expected.

As the central controller know this increase in load because of factory production schedule, at t=2 sec it decides to increase the reference value of DG 2 into 180 kW. It is obvious from that figures that DG 2 power go up and Master unit DG 1 power reduce and it will be prepare for next disturbance.

Similar simulation performed in case of load decreasing in bus 9 to its initial value. As it is shown in figure 7 the Master DG unit decreases its output power to balance the generation and demand and DG 2 work in the previous values of powers. In t=4 seconds the supervisory control decrease reference power values of DG 2 and hence the master unit power goes back to its initial value.

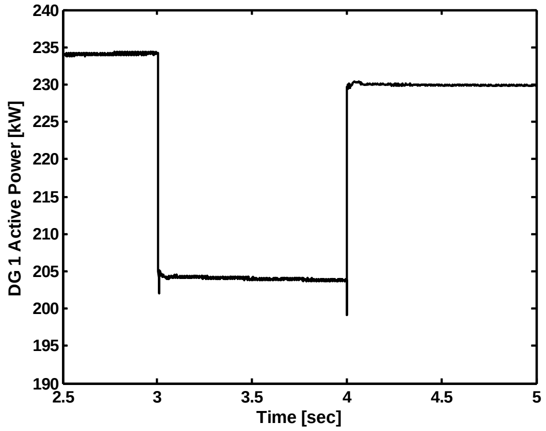

Figure 7: DG1 output power when load decrease

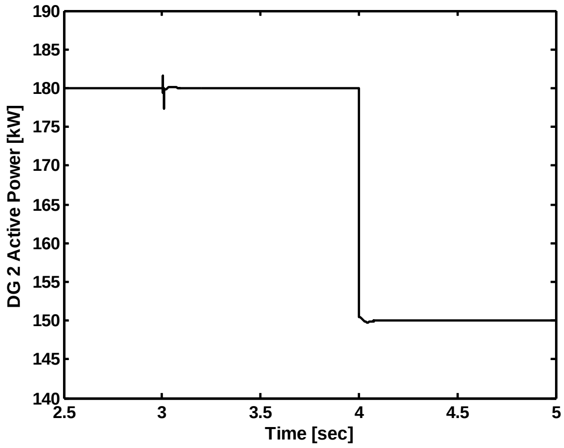

Figure 8: DG 2 output power when load decrease

Figure 9 show all buses voltages in this simulation period. As it can be seen, all buses voltages are at standard values (±5%). The figure shows that in this industrial network with short cables, regulating voltage in DG unit buses guaranteed standard voltage profile for other buses. If any bus voltage deviates from standard value then voltage regulation scheme and compensators should be considered.

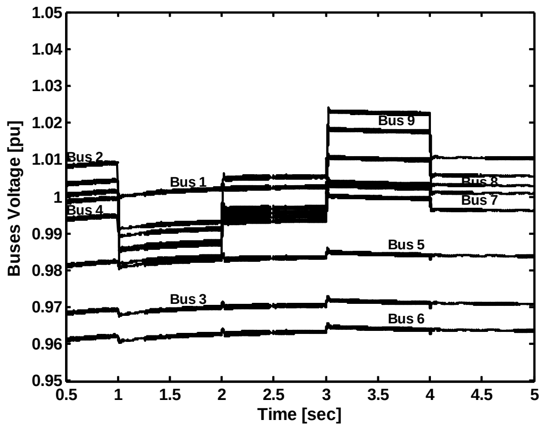

Figure 9: All buses voltage

Figures 10 and 11 show the reactive power output of each DG units. As expected and considered in system controller, the reactive power demand supplied by Master Unit and since the distances are short in the study system the voltage remain in standard value as shown in figure 9.

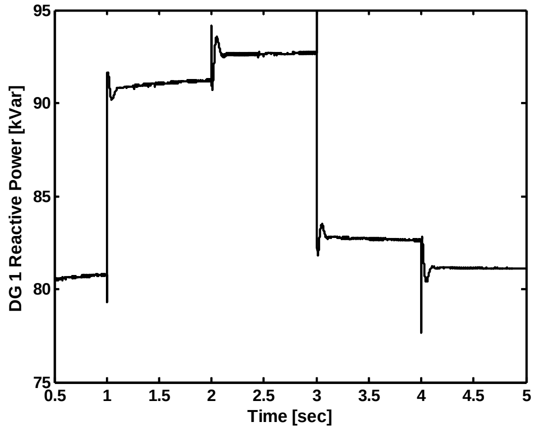

Figure 10: DG 1 output reactive power

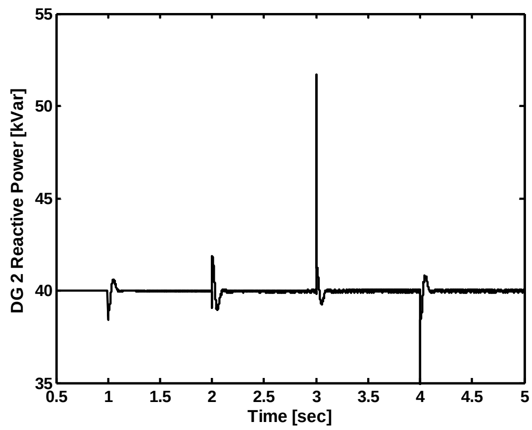

Figure 11: DG 2 output reactive power

As it is clear from the figures the proposed method for controlling DG unit is effective and can reply to the network needs during stand-alone mode but defining amount of reference voltage and power for each DG unit is a problem that must be solved for working perfectly and optimal the system. It mean that when utility is disconnected this control strategy guarantee that load supply continuously and when the utility come back the stand-alone system can reconnect to grid with consideration of synchronization.

6. CONCLUSION

This paper has presented a control strategy needed for successful load sharing and accurate voltage and frequency control in a stand-alone industrial network. To manage these goals, the system should include one large capacity inverter based energy storage unit which act as voltage and frequency reference and supporting the network during transients. The other DG units just supply reference value of power to network. The system with central controller that should adjust power reference of units is suitable for supplying reliable and high quality energy to important loads during outage of utility.

Simulation results showed that the system controller is able to keep the system stable and all buses voltage in standard value and the method guarantee continuity of power supply after utility outage.

APPENDIX

In this appendix study System parameters are given.
All lines are similar with the following data:
Cable Resistance: R= 0.164 ohms/km
Cable Inductance: L= 0.26 mH/km

Distribution Line Data

From Bus	To Bus	Length (m)
4	1	100
1	5	200
5	3	150
3	6	210
4	7	160
7	8	200
8	2	180
2	9	220

Buses Load Data

Bus No.	P (kW)	Q (kVar)
1	80	25
2	36	12
3	25	12
5	90	33
6	60	12
7	36	12
8	56	32
9	96	42

Distributed Generation Units Data

DG	Nominal Power (kVA)	Control Mode	P-Gain	I-Gain
DG 1	400	Vf	1.1	3.23
DG 2	280	PQ	6	0.12

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