# A Novel Control Strategy for Load Sharing of Low-Voltage Stand-alone Micro Grid

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***Abstract*—This paper proposes a novel control strategy for load sharing between several Distributed Generation (DG) units in a stand-alone micro grid (MG). The goal is, guide the generation unit in a MG to maintain the system frequency and voltage profile by responding to any load changes. This paper proposes a new droop control strategy to control the output power of DG units. To control the active power, the deviation of the voltage is used and the reactive power is controlled in a mode of constant power factor. Simulation results on IEEE 37 node test system show the ability of proposed droop control strategy to manage load sharing between DG units in a stand-alone mode of the distribution system.**

***Keywords—Distributed Generation (DG); Droop control; Inverter; Load Sharing; Micro Grid; Stand-Alone.***

## I. INTRODUCTION

A micro grid (MG) is a subset of a distribution energy system consisting of sufficient distributed energy resources (DERs) such as wind, solar and fuel cell to supply most or the entire local load. Thus, the MG is able to operate in grid-connected mode or run as an independent island, and can seamlessly transfer between these two modes [1]. Due to the expected high penetration of Distributed Generations (DG) in the distribution system [2]-[4] and the increasing competition amongst energy suppliers to secure more and more customers, using MGs with some DG unit in island mode is a valuable option to supply portions of the network or critical loads and is called Intentional Islanding in literatures [5]-[8].

The intentional islanding of a MG could potentially bring many benefits to the DG owners, Distribution Network Operator (DNO) and customers. Improving the reliability of supply, additional revenue to DG owners during network outage, and customer satisfaction due to reduction of the frequency and duration of interruptions from outages in the distribution network are some valuable benefits of using a MG in island mode [9]-[11]. The new IEEE Std. 1547-2003 states, as one of its tasks for future consideration, the implementation of intentional islanding of Distributed Generations [12].

However, before such a procedure can be implemented, the DG must be capable of maintaining the voltage and frequency within their standard permissible levels. Voltage and frequency control and load sharing control between DG units in an islanded network can be achieved in different ways that have been addressed in several literatures. In [13]-[21] 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 [20] showed this way have good results for controlling the power and voltage of each DG units. The main advantage of this method is that it lies on local variable and it is suitable for distribution system with long distance between DG units. However, as frequency will deviate after any load change, a secondary control loop is needed for stable and accurate frequency control.

In the conventional droops control concept that is derived from inductive coupled voltage sources combined with an inductance represents a high voltage line with a stiff grid, the reactive power is related to the voltage and the active power is related to the phase shift or respectively to the frequency. In a low voltage line in the distribution system, where resistive character is more than inductive behavior, the concept of droop can be changed which will be outlined and implemented in this paper.

In contrast, this paper proposes a method to control power sharing between DG units and maintaining voltage profile and stability of network. The work will be presented in six sections. Second section describes the characteristics and control scheme for inverter interfaced DG units. In third section, load flow and power relation in a distribution network will be described. In fourth section, the proposed system controller and the strategy for load sharing between DG units is presented. Fifth Section shows the study system configuration and simulation results and discussion. In the last section conclusion of work will be presented.

## II. CHARACTERISTICS AND CONTROL OF A MG WITH INVERTER INTERFACED DG UNITS

Inverter interfaced generation units have different characteristics to synchronous machines and so the power system consisting this equipment has different situation [22]. Some characteristics of this electrical generation units are:

- An inverter can operate as voltage sources (also current source) with independent control of the magnitude and phase of each phase that cannot performed with a synchronous generator.
- An inverter can produce absolutely sine wave or any waveform with the control of reference waveform but they produce high frequency distortion and need filtering.
- Overcurrent situation can be tolerated by inverters only in short periods so the current limiting action and short circuit protection must be considered.
- The active and reactive powers that are supplied by an inverter interfaced generation unit can be controlled independently with the parameter of the interfaced inverter.

The control strategy and filter has a significant effect on the performance of the system. There exist different control strategies for inverters and converters, such as PWM-based [4] and model predictive control-based [24]. A second-order LC filter is a good choice for overcoming the high order harmonic components [25] and it is used and designed in this study according to switching frequency of the inverters. Rahnamaee et al. [26] studied the pulse-width modulation and pulse-density modulation schemes to increase the overall efficiency of the inverter and generate high quality output line-frequency Sine waveforms.

Two inverter interface control strategies of generation unit under study in this paper are briefly explained in the following subsections (reader may refer to [27]-[28] for more details).

## III. THEORY OF POWER FLOW IN DISTRIBUTION SYSTEMS

The power flow into a line at point A, as represented in Fig. 1, can be expressed as equations (1) and (2) [29].

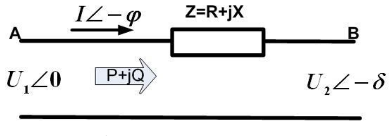


Fig. 1. Equivalent circuit of two buses and distribution line

$$P = \frac{U_1}{R^2 + X^2}[R.(U_1 - U_2\cos\delta) + X.U_2.\sin\delta] \quad (1)$$

$$Q = \frac{U_1}{R^2 + X^2}[-R.U_2\sin\delta + X.(U_1 - U_2.\cos\delta)] \quad (2)$$

Where $U_1$ and $U_2$ are the amplitude of buses voltage, δ is the power angle, and R, X are the resistance and reactance of distribution line respectively.

In low voltage distribution networks, lines resistance is more than their reactance [30]. So the imaginary part of the coupling impedance can be ignored and consequently the above power relation can be rewritten as (3) and (4):

$$P = \frac{U_1^2}{R} - \frac{U_1.U_2}{R}\cos\delta \quad (3)$$

$$Q = -\frac{U_1.U_2}{R}\sin\delta \quad (4)$$

For showing the relation of the power with the system parameter, let’s rewrite the above equation as equations (5) and (6):

$$p = \frac{u_1^2}{r} - m\frac{u_1^2}{r}\cos\delta \quad (5)$$

$$q = -m\frac{u_1^2}{r}\sin\delta \quad (6)$$

Where:

$$u_1 = \frac{U_1}{V_{base}}, u_2 = \frac{U_2}{V_{base}}, p = \frac{P}{S_{base}}, q = \frac{Q}{S_{base}}, \quad (7)$$
$$r = R\frac{S_{base}}{V_{base}^2}, and \quad m = \frac{u_2}{u_1}$$

And $V_{base}$ and $S_{base}$ are the base values for voltage and power in volts and VA.

If δ is kept constant and m changes, the active and reactive powers change linearly with approximately horizontal line showed in Fig. 2. Likewise, if m is kept constant, the curves in vertical direction will show the relationship between active and reactive powers. It is obvious from Fig. 2 that when m is constant the active power is approximately constant but reactive power can change with δ. In the other hand, with changing the m when δ is constant the active power can change and reactive power is approximately constant. This figure shows that the active and reactive powers can be controlled in an approximately independent channel with changing m and δ respectively.

Region of maximum acceptable power is determined with |p+jq|=1 circle because the maximum apparent power is rated power of the distribution line. Based on this region, maximum and minimum value of m and δ is determined as:

$$m_{\max} = \left|-r/u_1^2 - 1\right|, m_{\min} = \left|r/u_1^2 - 1\right| \quad (8)$$

$$\delta_{\max} = \tan^{-1}(-r/u_1^2), \delta_{\min} = \tan^{-1}(r/u_1^2) \quad (9)$$

In contrast, in a distribution network with high R/X ratio, active power can be regulated by the inverter output voltage amplitude, while reactive power can be controlled by the power angle which is the opposite to the conventional transmission networks with high X/R Ratio.

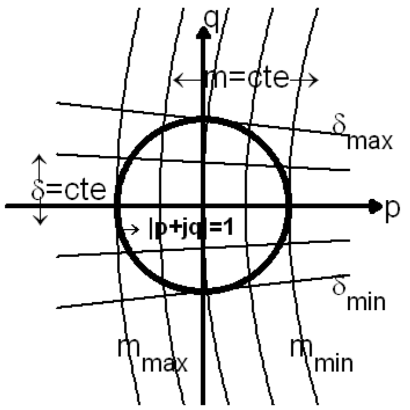


Fig. 2. P-Q diagram of a distribution line

## IV. Proposed Stand-Alone MG Controller

In a stand-alone distribution network, there are two main problems: the first problem is the presence of some low response and inertia less generation unit which necessitates putting some storage devices on dc link to realize fast load tracking. The second problem is the lack of frequency and voltage reference and so one or perhaps more than one of the DG units should play such a role and being a reference for voltage and frequency. Such a reference unit called Master DG unit in this study.

Therefore, the Master DG unit should be suitably sized to be able to perform desired regulation on power and voltage. The suitably sized storage included on the DC bus of this unit guarantees fast response to any change in power demand (fast load tracking) and stable ac voltage. The other DG units may work in constant power control scheme (PQ mode) to have contribution in stable load balance.

It can be noted that two main control strategies are possible for an islanded MG, single master operation (SMO) or multi master operation (MMO) [20],[31]. In case of SMO, the master unit output in normal condition should be far from its rating in order to compensate any load change. In case of MMO, there is more than one master unit which has the duty of regulating power and producing reference voltage and the whole system is more reliable.

In traditional power system with synchronous generators, the conventional droop method with P/f and Q/V droop function is used as load sharing control between generators and balancing the demand and generation [29]. However as showed in the previous section, in low voltage grid with high R/X ratio the active power and voltage are linked together and also the phase shift between end buses voltage and reactive power have direct relation. Based on this fact, the active power controller and reactive power controller of each non-master DG unit designed as follows in this study. It is obvious that all master DG units work in Vf control mode and they should supply the amount of regulating power in the system.

### A. Active Power Control

According to presented active power relation to voltage magnitude in distribution networks, a droop of active power with voltage can be used in low voltage MGs in order to guide DG units to contribute in power supply in island mode. Fig. 3 shows a curve of desired active power according to change in voltage magnitude.

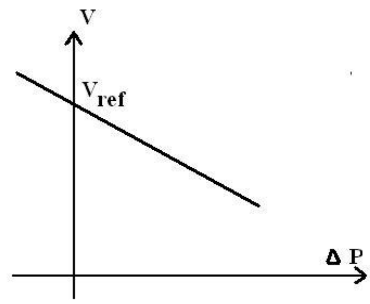


Fig. 3. Active power and voltage droop relation

As it can be seen from this figure, any change in the system load or configuration will change the voltage in all buses of the system. According to the amount of the change in bus voltage and the slope of the droop curve, each DG unit power reference will change and the unit will contribute in power supply. Adjusting the initial power reference, the slope of curve (droop coefficient), and the reference voltage ($V_{ref}$) can determine the power sharing among several DG units in the system.

Since the change in voltage in generation unit near disturbed load is more than other far units, it is obvious that the power takes the closest path and the loss of system is minimized in this manner. Block diagram of the control scheme for defining the power reference of the DG units according to this droop scheme is presented in Fig. 4.

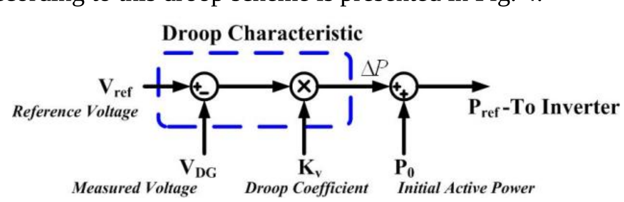


Fig. 4. Block diagram of reference power deviation according to droop curve

### B. Reactive Power Control

Due to the lack of initial phase in the system, using phase difference for reactive power control is not applicable. This is for the reason that the frequency can be used as a droop parameter for reactive power control. But using frequency for droop function yield in frequency deviation in the system and need for secondary control loop for maintaining the frequency in normal value. So, in this study it is assumed that all non-master inverter units work in constant power factor and the reactive power change with changing in the active power of units accordingly. If the voltage exceeds from the normal values, $V_{min}$ and $V_{max}$, the power factor will change and the inverter will absorb or inject more reactive power to regulate the voltage at normal range. Fig. 5 shows this control strategy for the reactive power. It is obvious that any deviation between demand and generation in both active and reactive power will be balanced with the master unit.

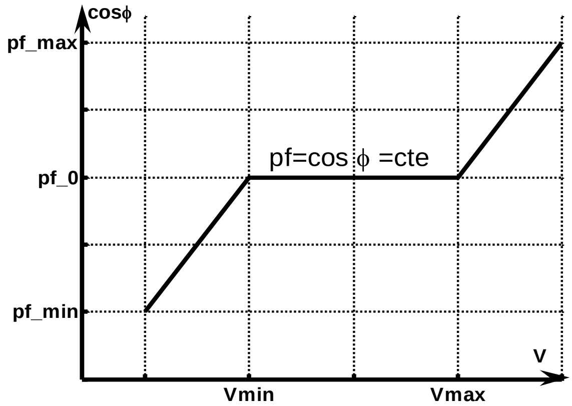


Fig. 5. Reactive power control scheme

### C. *Proposed Control Strategy*

In summary, the proposed strategy for controlling power sharing between DG units with this droop method is shown in Fig. 6.

At first it is assumed that all the units in the stand-alone system operate below their ratings. Any change in loads demand, system configuration, or generation units will cause voltage deviation in all buses. The control system of all units will response to this change and the reference powers will change and all units will contribute in the system load. The master unit which has storage device can reply instantly to the change and regulate the active and reactive power of system while the other units are preparing the desired power slowly depend on their generation technology. It is evident that each DG unit work and control with its local variable and the controller should consider the inverter switches ratings.

During the load change and time need for other DG units to produce the power, the Master DG unit should be able to produce extra load demand.

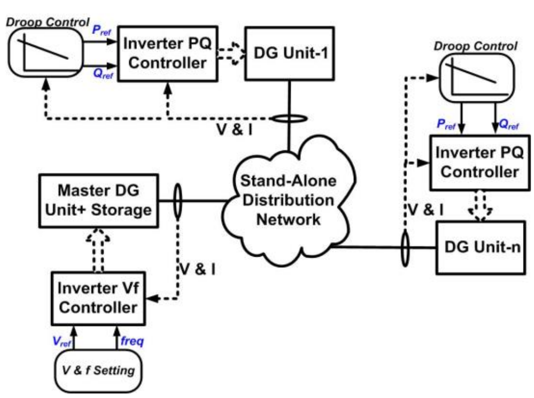


Fig. 6. Control scheme of system with one master unit

So, the capacity of storage device should be determined with consideration of the amount of the load change, speed of controller, and DG units' response time. Authors in [27], [32] and [35] have described how much storage is suitable and how to design it.

Some cases such generation outage or demand greater than total DG units powers, can cause under voltage in the system and so load shedding scheme should be used. In this study, it is considered that the load and generation are balanced and it is no need for load shedding.

## V. STUDY SYSTEM AND SIMULATION

The proposed load sharing control strategy has been experienced on the IEEE-37 node test system [33]. The system consists of four DG units which are connected to the system through voltage source inverters in buses number 23, 13, 2, and 30. Initially load flow calculation shows the best value of active and reactive power for each unit to have normal voltage in all buses. Readers may refer to [33] for more details about system parameters and buses load demand data.

When the utility is available the Distributed generation units (DG 1-DG 4) produce some part of energy in order to reduce demand charge. The system is considered to become islanded from the main grid after a fault for the utility or a scheduled disconnecting from utility via turning the main switch in bus 1 off.

The previously discussed concepts are now applied in the study system to explain more effectively the mechanism of generation control in a standalone power distribution system. Simulation test bed using MATLAB/SIMULINK is constructed for the AC 4800 V (LL)/50 Hz system . It is considered that DG 1 is the Master DG unit and it acts like a synchronous generator for producing voltage and frequency reference because it has storage device to overcome load change rapidly. The other units synchronize themselves with the main unit via PLL and work at PQ mode of operation and their reference power can change with droop control scheme. The droop factor for each unit is defined proportional to its rating that specified in TABLE I. in appendix. For simplicity and focus on control strategy, it is considered that all units are battery inverter interfaced and they have enough storage to reply to any change in loads. In realistic system where the units have generation system like fuel cells, photovoltaic array, wind turbine, and etc, the units can reply to changes in sluggish manner and so the storage device should perform power regulation during transients.

TABLE I. DISTRIBUTED GENERATION UNITS DATA

| **[1] DG Unit** | **[2] DG1** | **[3] DG2** | **[4] DG3** | **[5] DG4** |
|---|---|---|---|---|
| **Rated Power (kVA)** | [7] 400 | [8] 250 | [9] 350 | [10] 260 |
| **Initial Active Power (kW)** | [12] - | [13] 200 | [14] 220 | [15] 200 |
| **Initial Reactive Power (kVAR)** | [17] - | [18] 80 | [19] 150 | [20] 50 |
| **Droop Coefficient-$K_V$** | [22] - | [23] 200 | [24] 140 | [25] 190 |
| **Reference Voltage-$V_{ref}$** | [27] 1 | [28] 1.005 | [29] 1 | [30] 1.001 |

The system is simulated under insertion of a load in the system and the simulation results of system will explain in three cases.

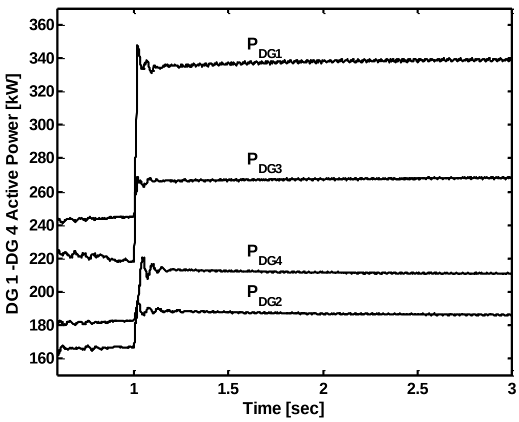


Fig. 7. DG 1-DG 4 active output powers

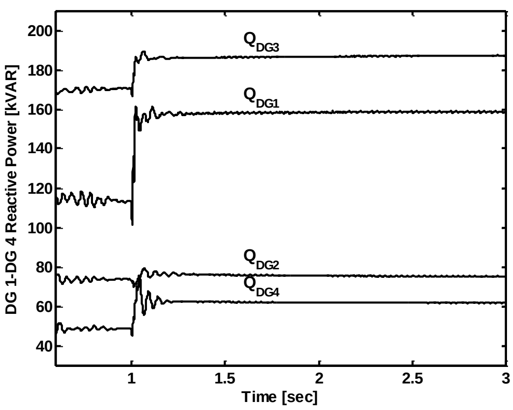


Fig. 8. DG 1 – DG 4 reactive output powers

## A. Initiate the System

Initially it is considered that the system works with reference value of load flow calculation and droop factors which is showed in table A2 in appendix. It can be seen from Fig. 7 and Fig. 8 that in this case the controllers adjusted output power of DG 2-DG 4 in desired value and as expected remaining needed power supply by Master unit, DG 1 [36].

## B. Inserting a Load

At t=1 seconds a heavy load of 200 kW and 80 kVAR inserted in bus 14 and it can be seen from Fig. 7 and Fig. 8 that the increased power divided between DG units proportional to their rating and the distance between load and the unit. As DG 2 is very far from the load point (bus 14), this unit has few contribution to the load variation as it is expected. Fig. 9 shows the generation units buses voltage. It can be seen from the figure that the closer unit to load point has the more voltage deviation and also all voltage is remained in allowable range with controlling the active and reactive powers of generation units.

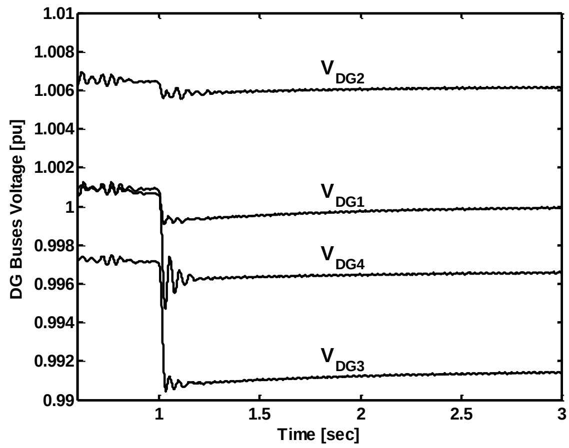


Fig. 9. DG 1 – DG 4 buses voltage

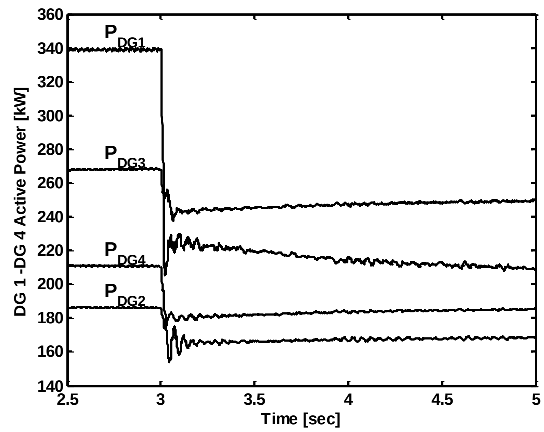


Fig. 10. DG 1-DG 4 active output powers after removing load

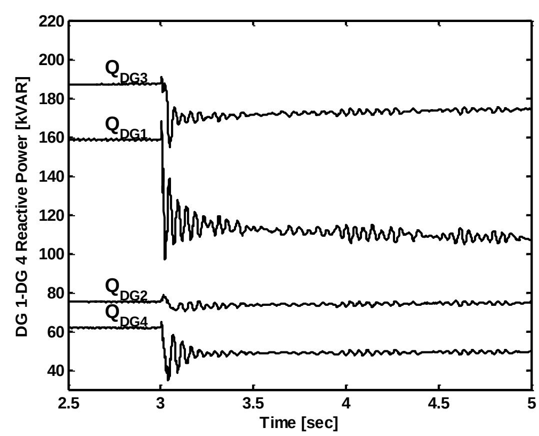


Fig. 11. DG 1– DG 4 reactive powers after removing load

## C. Removing the Extra Load

Similar case happens in 3 second when the load gets out of the system and all units' power reduce to initial value. Fig. 10

and Fig. 11 show active power and reactive power of DG units in this case.

In this study the droop factors are chosen proportional to the units rating. Each unit adjusts its output power according to its rating and distance to point of load change. The droop factors are constant and there is no necessity to change them in different load profile on-line. In other hand, as different load profile cause different power references for all DG units and the power sharing might not be optimal, therefore the droop characteristics can be changed to guarantee optimal situation in the system.

Fig. 12 shows the DG units buses voltage and it is obvious that removing the load cause voltage rise and the controller use this voltage change and adjust the power reference of all units. In the simulation results, the power oscillation at the beginning of the load change is observed that are due to dynamic of the system and controllers. In the other hand, there are several nonlinear elements like switches and saturation blocks in the system. This nonlinearity causes different responses in different working conditions. Therefore, the oscillation seems to be larger at the light load than at the heavy load. This oscillation can be reduced if an adaptive controller is designed to compensate the response according to the system dynamic at any working state.

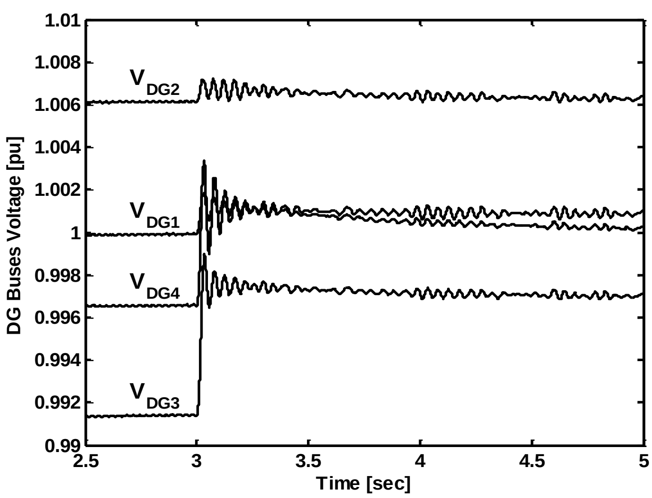


Fig. 12. DG 1 – DG 4 buses voltage after removing load

Fig. 13 shows some remote buses (Buses Number 18-21-24-27-29-34-35-36-37) voltages respectively. As it can be seen, in this distribution network with short lines, controlling voltage in DG unit buses maintain the voltage in all buses at normal range. If any voltage exceed from normal limit (±5%) then compensation scheme or readjustment of droop parameter for all unit is needed.

It should be noted that the proposed method doesn't guarantee that the voltage profile after load sharing is the best or the optimal one. As described before, the voltage is controlled according to droop characteristics and additional control loop exists that controls the voltage, if exceeds from criterion of 5% by the reactive power injection or absorption. It is obvious that if any DG unit reaches to its rating limit, it can not adjust the voltage and this may cause abnormal voltage. In conventional power system there is load forecasting strategy that defines new set points (Droop Characteristics) for each power plant before any load change and this method also can be used in this system.

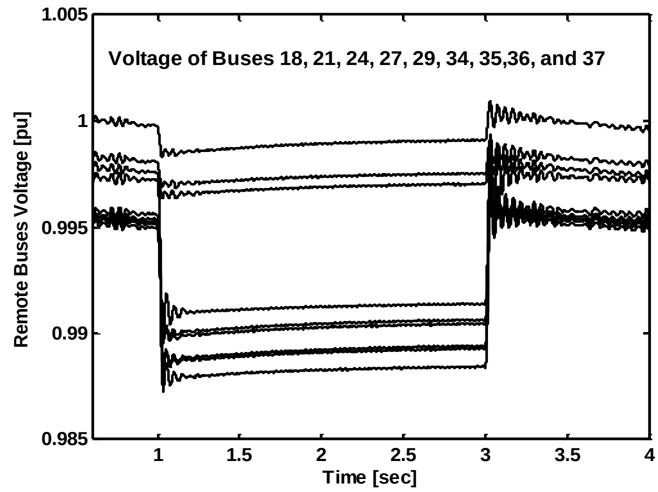


Fig. 13. Remote buses voltage

As it is clear from the simulation results, the proposed method for controlling DG units is effective and can reply to the network needs during islanding from the main grid and the scheme can guarantee continuity of power to loads.

## VI. CONCLUSION

This paper has presented a control strategy needed for successful load sharing and accurate voltage and frequency control in a stand-alone distribution network. For this aim, there should be some DG units responsible for demanding power and some of them responsible for perturbed conditions to inject the regulating power. It means that some of the units connected through the voltage source inverters should be PQ controlled and some should be in the Vf controlled mode.

The proposed method suggests that divide the responsibility of injecting the regulating power to all the DG units in the system similar to what exists in traditional power systems consist of multiple synchronous generators. In the proposed method for load sharing control in stand-alone power distribution systems is based on droop between active power and voltage and also the reactive power control in constant power factor mode. Simulation results showed that the system controller is able to keep the system stable and all buses voltage in standard value and the power is shared between DG units and the method of control guarantee continuity of power supply after islanding from main utility grid.

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