Generation Control in Small Isolated Power Systems

M. Milošević, *Student Member IEEE*, G. Andersson, *Fellow IEEE*

***Abstract*—Recently, interest in isolated power systems is rapidly increasing. This interest is due to the fact that larger power plants are economically unfeasible in many regions due to increasing system and fuel costs. When the system operates in isolation then load tracking problem will arise which can cause voltage and frequency instabilities. One possible solution to keep power balance in the system and to have generation control is to use DC battery storage. This paper present a study of the generation control in small isolated power network based on grid voltage control and the storage frequency control.**

***Index Terms*— frequency control, voltage control, island network**

I. Introduction

NOWDAYS there is the upward tendency to transition from a centralized power producing system to small isolated power systems for rural and remote areas. In these systems the main power producers are the renewable sources of energy (e.g, photovoltaic cells (PV), fuel cells, wind power etc.) in combination with diesel generators. These small power producing networks need a distributed and autonomous generation control.

They are generally connected to the grid at substation or customer loads. Many of them generate power in the form of direct current (e.g. PV, fuel cells) or in the form of alternate current at a frequency different from the required 50 Hz (e.g. wind generators, microturbine). Therefore, the system containing these sources requires a power electronic interface.

Interest in small isolated power systems is also attractive for power utility companies, since they can help in improving the power quality and power supply flexibility. Also, they can provide spinning reserve and reduce the transmission and distribution costs, and can be used to feed the customers in the event of an outage in the primary substation [1].

However, in an isolated system based on a single renewable energy source, a system with only wind power has a higher availability than a solar based one [2]. Adding storage capability increases the availability more for solar-based systems.

When there is unbalance between active power production and active power load demand the frequency deviates from its nominal value. Therefore, the isolated system should be able to maintain frequency in the acceptable operating range to ensure power quality.

In [3] the authors studied the characteristics of Demand Based Frequency Control (DBFC). It utilizes control devices which will turn off (on) the machine/appliance in response to frequency deviations in order to restore the supply/demand balance, and will turn them back on (off) at a time when the frequency deviations are in the acceptable range.

The isolated network model is given in Fig. 1. This network consists of a synchronous generator and renewable energy source, connected through the voltage source inverter, as the sources of energy, and the load.

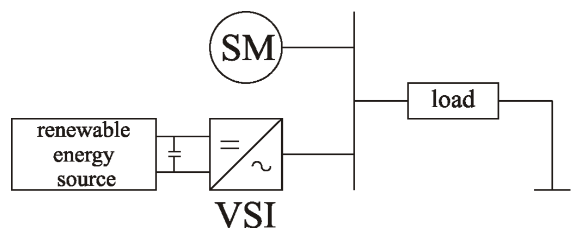

Fig. 1. Model of small isolated power network

This paper presents the theoretical analysis and simulation results of the small isolated power network consisting of the synchronous generator, renewable energy source (PV cells) and energy storage interfaced through the inverters. The purpose of this paper is to study possibilities for small isolated power systems with respect to generation control under conditions of the load disturbance.

Generation control can be done either by voltage or by frequency control. These two different methods for the generation control are presented. One method uses the grid voltage control and the second uses the frequency control of the storage.

The rest of the paper is organized as follows-the system description is given in Section II, followed by the description of the system with storage in Section III. The active power voltage and frequency control are described in Section IV. Simulation results are presented in Section V, followed by conclusion in Section VI.

II. System Description

The main idea for the examination of this network is that renewable energy based units are not controllable and

M. Milosevic is with Power System Laboratory of Swiss Federal Institute of Technology (e-mail: milosevic@eeh.ee.ethz.ch).

G. Andersson is with Power System Laboratory of Swiss Federal Institute of Technology (e-mail: andersson@eeh.ee.ethz.ch).

therefore cannot participate in the generation control. Renewable energy sources usually generate DC current and/or DC voltages. Therefore, this source is modeled as a DC current source. In other words, it can be assumed that the current of energy source flowing into the DC link is nearly constant during the studied period of time.

A. Model of the Synchronous Generator

The detailed model of the synchronous generator can be found in [4]. The generator is modeled using the following stator winding equations:

$$\begin{aligned} U_{dr} &= -R_a I_{dr} + x'_q I_{qr} + E'_d \\ U_{qr} &= -R_a I_{qr} - x'_d I_{dr} + E'_q \end{aligned} \tag{1}$$

where, R_a is the stator winding resistance, x'_d and x'_q, and E'_d and E'_q are d-axis and q-axis transient resistances and voltages, respectively.

The rotor winding equations are given by:

$$\begin{aligned} T'_{q0}\frac{dE'_d}{dt} + E'_d &= (x_q - x'_q) I_{qr} \\ T'_{d0}\frac{dE'_q}{dt} + E'_q &= E_f - (x_d - x'_d) I_{dr} \end{aligned} \tag{2}$$

where, T'_{d0} and T'_{q0} are the d-axis and q-axis open circuit transient time constants, and E_f is the field voltage.

Torque equation and equation of motion are given by (3) and (4), respectively:

$$T_{el} = I_{dr} E'_d + I_{qr} E'_q + (x'_q - x'_d) I_{dr} I_{qr} \tag{3}$$

$$\frac{d}{dt}\frac{\omega - \omega_e}{\omega_b} = \frac{1}{2H}(T_{mech} - T_{el} - D\frac{\omega - \omega_e}{\omega_b}) \tag{4}$$

where, T_{el} and T_{mech} are the electrical and mechanical torque, D is the damping constant, H is the inertia constant, ω_b is the base frequency and is equal 1 p.u., ω_e is the excitation frequency (assume that $\omega_e = \omega_b$) and ω is the rotor frequency.

B. The Average Model of the Voltage Source Inverter

The average large signal model of the voltage source inverter (VSI) is used [5]. The switching averaging in this model is performed on a phase-leg basis. The phase leg is composed of two switching cells. It has a current source on one side (or an inductor) and a voltage source (or a capacitor) on the other (Fig. 2).

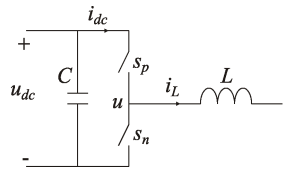

Fig. 2. Phase leg in voltage source inverter

There are switching constraints that include capacitors (or voltage sources) which cannot be short-circuited, and inductances (or current sources) which cannot be open-circuited. Therefore, the two switching cells of the phase leg should be complementary. That means that only one of the switches can be closed at any time. In other words, in order to prevent the current source to be open-circuited, one of the switches has to be closed at any time. Let T be the switching period and m_p be the duty cycle of the top switch s_p, and m_n be the duty cycle of the down switch s_n. It can be obtained the voltage and current relationships in average, assuming the voltage u_{dc} and the current i_L are continuous:

$$u = m_p u_{dc} + m_n u_{dc} \tag{5}$$

$$i_{dc} = m_p i_L + m_n i_L \tag{6}$$

By connecting three average phase legs the average model of three-phase VSI can be obtained (Fig. 3).

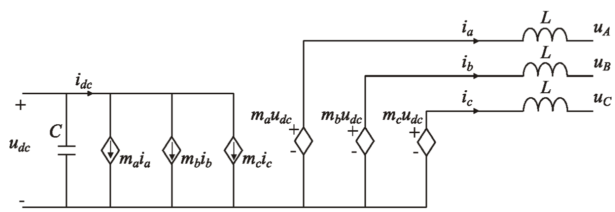

Fig. 3. Average model of three phase VSI

Mathematical equations for this model are:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L}\begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} u_{dc} - \frac{1}{L}\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \tag{7}$$

$$i_{dc} = m_a i_a + m_b i_b + m_c i_c \tag{8}$$

The variables in the stationary reference frame (X_{abc}) are usually transformed into the rotating coordinates (X_{dq}) using the following equation:

$$X_{dq} = T X_{abc} \tag{9}$$

where T is the transformation matrix given by:

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (10)$$

Applying (9) and (10) to (7) and (8), the average model of the VSI in rotating reference frame is given by:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{L}\begin{bmatrix} m_d \\ m_q \end{bmatrix} u_{dc} - \frac{1}{L}\begin{bmatrix} u_d \\ u_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (11)$$

$$i_{dc} = m_d i_d + m_q i_q \quad (12)$$

The DC voltage u_{dc} is calculated using the fact that VSI should not have influence in the active power transmission, i.e. active power at the input ($P_{in} = u_{dc} i_{dc}$) of the VSI should be equal to the active power at its output ($P_{out} = u_d i_d + u_q i_q$). Therefore, the DC voltage link equation is given by:

$$C \frac{du_{dc}}{dt} = I_{in} - \frac{u_d i_d + u_q i_q}{u_{dc}} \quad (13)$$

C. Dynamic Load Model

Assuming first order dynamics, Hill and Karlsson in [6] and [7] proposed that the load active and reactive power (P and Q respectively) can be given as solutions of the following differential equations:

$$T_p \frac{dP_r}{dt} + P_r = P_s(u) - P_t(u); \quad P_l = P_r + P_t(u) \quad (14)$$

$$T_q \frac{dQ_r}{dt} Q_r = Q_s(u) - Q_t(u); \quad Q_l = Q_r + Q_t(u) \quad (15)$$

where P_r and Q_r are the corresponding load states, T_p and T_q are the load recovery time constants. P_s, Q_s and P_t, Q_t are the steady state and transient load characteristics, respectively. They are given as a function of the node voltage u:

$$P_s(u) = P_0(\frac{u}{u_0})^{\alpha_s}; \quad P_t(u) = P_0(\frac{u}{u_0})^{\alpha_t}$$

$$Q_s(u) = Q_0(\frac{u}{u_0})^{\beta_s}; \quad Q_t(u) = Q_0(\frac{u}{u_0})^{\beta_t}$$

(16)

where, α_s, α_t, β_s and β_t are parameters that represent load static and dynamic voltage dependences, and P_0, Q_0 and u_0 are respective variables at the initial operating condition.

The block diagram representation of the dynamic model (active power given by (14)) is given in Fig. 4.

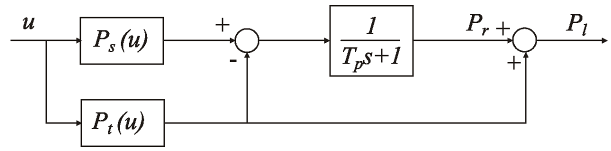

Fig. 4. Block diagram representation of the dynamic load model

III. Small Isolated Power System with Storage

When the power system operates in isolation, load-tracking problems will arise because the renewable sources of energy are inertia-less. Grid power systems have storage in the form of the generators' inertia, which results in a small frequency deviation [8] when a new load comes on line. However, this is not the case in small isolated power system with inverter interfaced renewable energy sources. They cannot rely on generator inertia and must provide some form of the power storage to keep the initial power balance.

One possible solution is to use a DC battery storage connected through the inverter with the system. The controller is needed for controlling the possible load power demands (to ensure $P_{storage} = P_{load} - P_{vsi} - P_{sm}$), assuming that power demand from the storage is always within its capability (Fig. 5).

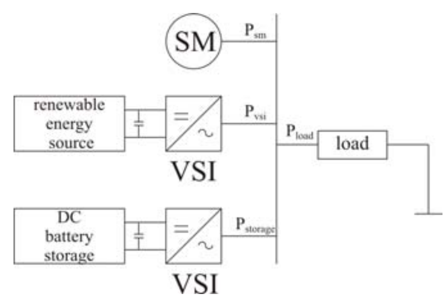

Fig. 5. Isolated power network with DC battery storage

IV. Active Power and Voltage Control

A. Active Power Control

Assuming that there is no battery storage connected at the network, the total energy delivered by the PV cells may overcharge the DC capacitor. This energy should be injected into the system by controlling the active power fed through the VSI. This implies having constant active power fed to the load through the VSI. In this case, the power consumption of the load is not controlled by the VSI. Therefore, the active power consumed by the load must be compensated with generator production.

If the type of the renewable energy source is photovoltaic, then it can be modeled as a constant DC current source which feeds the VSI, during studied time frame. This is true since the power variation frequency of the source is very small compared with the ac network frequency [9]. Here, acting on the modulation index m_d controls the active power. Also, the

VSI reactive power is adjusted to be zero, since the photovoltaic source of energy does not produce reactive power, by the acting on the modulation index m_q. The control blocks are given in Fig. 6.

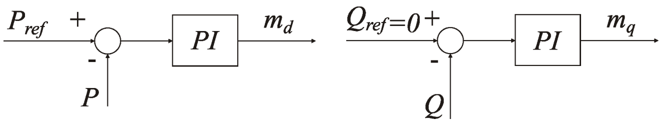

Fig. 6. Control blocks for the model with constant DC current source

This type of control would cause the frequency to change in the generator since the generator should compensate the load active power consumption. It will also imply change in the grid voltage due to the load voltage dependency given by (14).

B. Grid Voltage Control

Both the magnitude and the phase of the grid voltage ($\underline{u}$) can be controlled. In order to control the grid voltage, VSI output voltage ($\underline{u}_{VSI}$) should be adjusted by acting on the modulation index of the VSI ($\underline{m}$). In this paper just the magnitude of the grid voltage is controlled. This implies that one of the components of the modulation index should be set to an arbitrary value (we set m_q to zero). Also, this implies that DC voltage u_{dc} should be controlled. Therefore, the DC current source feeding the VSI is no longer a constant. Adjusting the DC current source infeed also adjust the DC voltage control. Consequently, the input active power into the VSI is not constant, but it compensates the power consumed by the load. And, controlling the magnitude of the grid voltage is done by adjusting the modulation index m_d, since $m_q = 0$. The control blocks are given in Fig. 7.

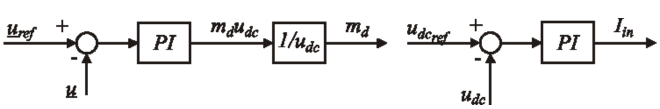

Fig. 7. Control blocks for the model with controllable DC current source

C. Load/Generation Control

There are two possible methods used to control the load/generation balance in this system. The first method is to control the magnitude of the grid voltage. Fig. 6 gives the control blocks. Acting on the modulation index of the storage VSI controls the voltage. The second method is to control the frequency of the storage current. The control block is given in Fig 8, where the reference value for the magnitude of the grid voltage is the output of the PI controller.

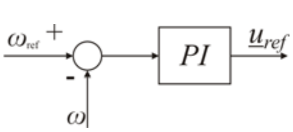

Fig. 8. Control block for the controlling storage frequency

V. Simulation Results

Simulations are done using SIMULINK. Parameters used for simulations are given in Table I. The values for the load parameters T_p, T_q, α_s, α_t, β_s and β_t are chosen according to [7,10,11]. The load disturbance is simulated by changing the value of P_0 (in (16)) by adding 5% after 40 seconds, then by subtracting 5% after an additional 40 seconds and by adding 10% after an additional 40 seconds.

Different active power, voltage and frequency control schemes are simulated. If the load demand is not equal to the sum of the power generated by the generator and the power generated by the PV, it is possible that the frequency will exceed its acceptable limits and it would cause the system to collapse. Therefore, it is required to have voltage and frequency control in the system, so that they are fixed to their nominal values after a short transient.

TABLE I
PARAMETERS USED IN NETWORK MODEL

Symbol	Quantity	Value
R_a	Stator winding resistance	0.0048 p.u
x_d	d-axis inductance	1.79 p.u
x_q	q-axis inductance	1.66 p.u
x'_d	d-axis transient resistance	0.355 p.u
x'_q	q-axis transient resistance	0.57 p.u
T'_{d0}	d-axis open circuit transient time constant	7.9 sec
T'_{q0}	q-axis open circuit transient time constant	0.41 sec
H	Inertia constant	3.77 p.u
$Linv$	Coupling inductance	0.001 p.u
C	DC capacitance	0.0022 p.u
Tp, Tq	Load recovery time constants	100 sec
αs	Static active power load dependency parameter	1.8
αt	Transient active power load dependency parameter	2
βs	Static reactive power load dependency parameter	4
βt	Transient reactive power load dependency parameter	2.5

A. Simulation Results with VSI Active Power Control

In Fig. 9 it can be seen that when the active power fed by VSI is kept constant, the electrical torque of the generator follows the load consumption change which implies the frequency also changes. Also, it can be seen that the node voltage is changing due to the load dependency of this voltage, as it is mentioned above.

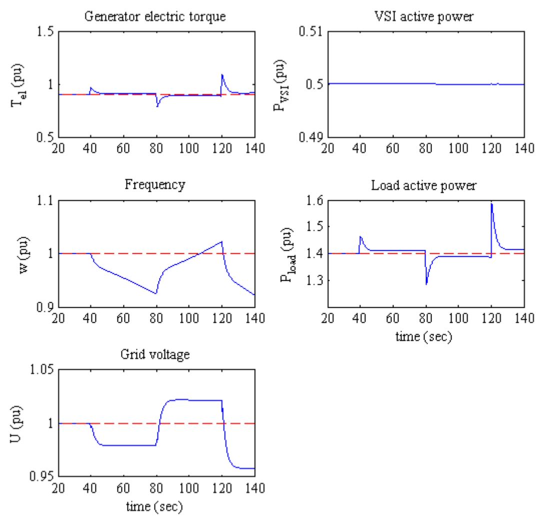

Fig. 9. Simulation results when the active power fed to the load through the VSI is controlled (dashed lines present the system with initial load, and solid line with load changes)

B. Simulation Results with Grid Voltage Control

The simulation results of the network controlling the grid voltage are given in Fig. 10. It can be seen that the grid voltage is kept constant which indirectly implies the control of the frequency of the generator, since the active power load consumption is compensated by the controllable DC current source, not by the generator's production.

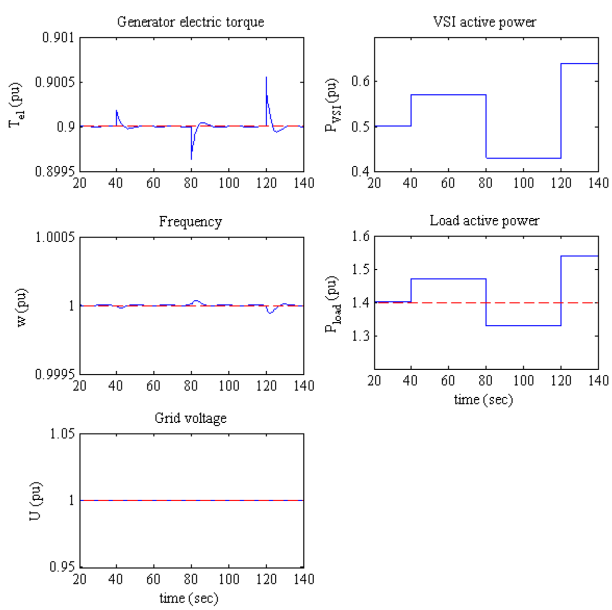

Fig. 10. Simulation results for grid voltage control with controllable DC current source infeed into VSI

C. Simulation Results with Storage

One possible solution to have frequency and voltage control in the network is to have storage connected to the network. The active power balance is kept by controlling the network current frequency and controlling the grid voltage through the active power taken from the storage. Simulation results for this method of controlling the frequency by controlling the grid voltage using the battery storage in the system are given in Fig.11.

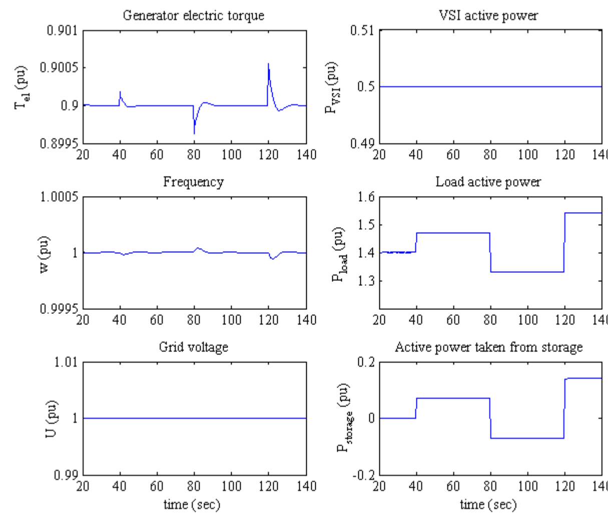

Fig. 11. Simulation results with grid voltage control when there is a DC battery storage in the isolated network

Similar behavior of the system is obtained if there are oscillations in the PV active power production (Fig. 12).

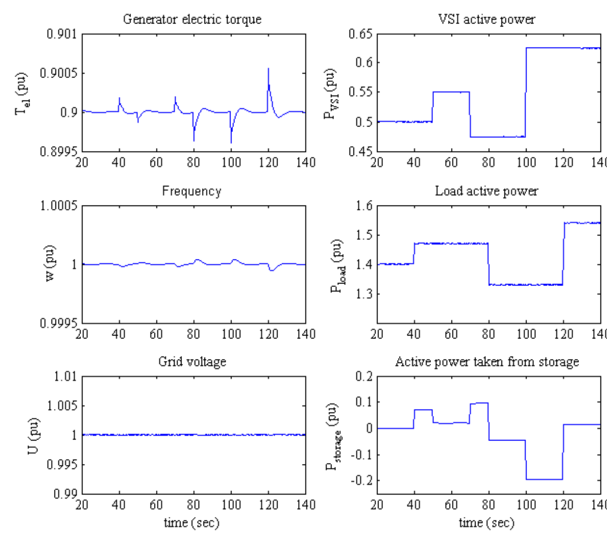

Fig. 12. Simulation results with oscillation in PV active power production

By controlling the storage current frequency it can be seen that frequency of the generator is also controlled, while the grid voltage requires more time to get back to its nominal value (Fig. 13).

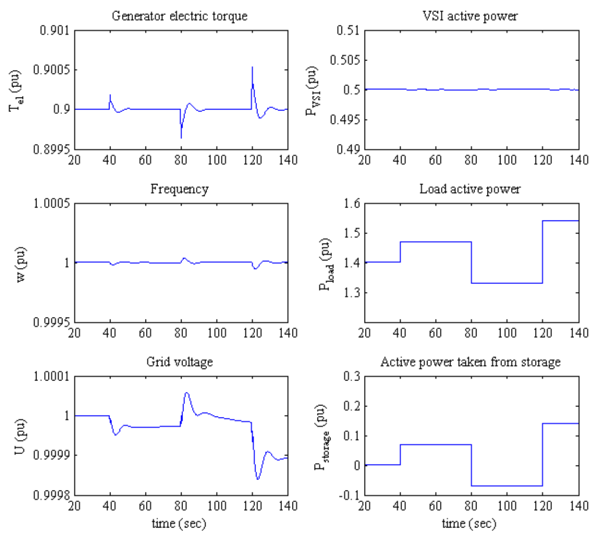

Fig. 13. Simulation results when the storage current frequency is controlled

Comparing Fig. 11 and Fig. 13 it can be seen that the method that uses the grid voltage control brings the generator frequency to its nominal value faster. On the other hand, the method that uses the frequency control of the storage current needs more time to bring the grid voltage magnitude to its nominal value.

Fig. 14 shows a comparison between these two methods for the load/generation control. It can be seen that the voltage control method needs less time to bring the system frequency back to its nominal value.

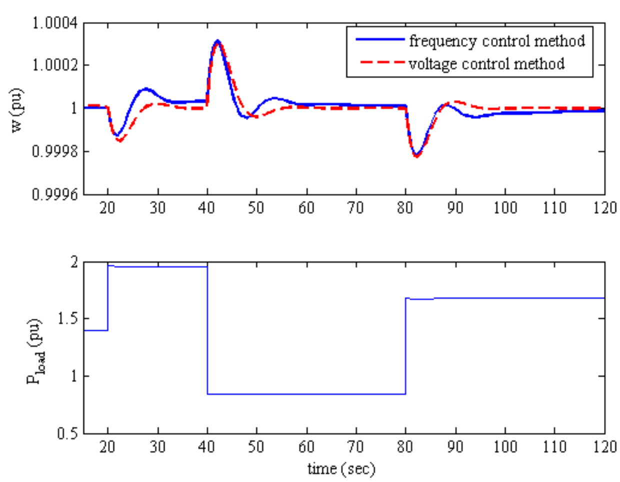

Fig. 14. Comparison between two methods for the load/generation control

VI. Conclusion

Two different methods for generation control in a small isolated power network are presented. The grid voltage control method has better performance with respect to the time needed for the system recovery after the load disturbance. The frequency control method needs more time to bring the voltage back to its nominal values after a load disturbance. One possible solution to control load/generation balance is to have DC battery storage.

Acknowledgment

Financial support from the Alliance of Global Sustainability (AGS) is gratefully acknowledged.

References

[1] M. N. Marwali, Jin-Woo Jung; A. Keyhani, *Control of distributed generation systems - Part II: Load sharing control*, pp. 1551- 1561.

[2] J. W. Black, M. Ilic, *Demand-based frequency control for distributed generation*, IEEE PES Summer Meeting, 21-25 July 2002, Vol.1, pp. 427 – 432

[3] J.S.G. Ehnberg, M.H.J.Bollen, *Generation reliability for small isolated power systems entirely based on renewable sources*, IEEE PES General Meeting, June 2004, Vol.2, pp. 2322 – 2327.

[4] Chee-Mun Ong, *Dynamic Simulation of Electric Machinery*, Prentice Hall, 1998.

[5] Z. Ye, *Modelling and control of parallel three-phase PWM converters, PhD dissertation*, Virginia Polytechnic Institute, September 2000.

[6] D. J. Hill, *Nonlinear dynamic load models with recovery for voltage stability studies*, *IEEE Transaction on Power Systems* 8 (1), 1993, pp. 166-176.

[7] D. Karlsson, D. J. Hill, *Modelling and identification of nonlinear dynamic loads in power systems*, *IEEE Transaction on Power Systems* 9 (1), 1994, pp. 157-166.

[8] P. G. Barbosa et al., *Novel control strategy for grid-connected DC-AC converters with load power factor and MPPT control*, http://www.solar.coppe.ufrj.br/rolim.html

[9] R. Lasseter et al., Integration of distributed energy resources, CERTS, April 2002. ; http:/certs.lbl.gov/pdf/LBNL_50829.pdf

[10] W. Xu, Y. Mansour, *Voltage stability analysis using generic dynamic load models*, *IEEE Transaction on Power Systems* 9 (1), 1994, pp. 479-493.

[11] P. Kundur, Power system stability and control,McGraw-Hill, Inc., 1994.