

# OPERATION OF POWER SYSTEM ISLANDS

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## ABSTRACT

*In this paper, a method for continuity of electrical supply to a region after disconnecting from the main network is presented. In this method, the island is protected from the total loss of supply at the price of shedding some load. In the proposed method of this paper, the case of control of the island without using an explicit communication is considered. The indirect communication between generators and loads uses frequency of the island and knowledge of droop characteristic of the generators. The process of surviving the separation and controlling the island is validated on a test system.*

## 1. INTRODUCTION

Recently the use of distributed generation is growing in the power systems and is often motivated by co-generation opportunities in the electricity market [1-2]. The distributed generation usually operates in parallel with the main networks and it can increase the reliability of providing energy for the customers in that area. This additional benefit occurs if the distributed generation can continue to supply customers when the island is separated from the network.

Load shedding and load restoration has been studied in many papers such as [3-6]. However they did not fully consider how an island can survive when there is no communication between the loads and generators. In the report published by UK Department of Trade and Industry [7], the islanding of the distributed generation is studied. This report addresses the protection requirements of the islanded network. Frequency control using droop is studied but there is no coordination with load control.

In this paper a method is suggested for control of the island supplied by partly from the mains and partly from local distributed generators after disconnecting the network from the mains. In this method, an algorithm presented to take necessary measures when the island is disconnected from mains in order to protect local network customers from blackout by appropriate load shedding. The balance of supply and demand can also provide some opportunities for restoring some loads. The proposed strategy is based on the case when there is no communication between the distributed generators or the loads in the electrical island. In the real power systems, where a region is connected to the main networks, the degree of the communication varies across the range of zero communication to fully central communication. It is obvious that as the degree of communication increases, the price rises. Thus, there is a trade off between the degree of communication and the price. Regarding the situation that we are dealing with, we could accept a

system with degree of communication. Also for a remote region, it might be not economical to use a communication system. Therefore, for this circumstance, the case of zero communication of the tailored control for deliberate electrical island is recommended.

Considering the zero communication case for surviving the region after disconnecting from the mains, is the task of this paper. Other cases of communication between the generators are tasks for the future research. The suggested algorithm is validated through a simulation on a test system. The outcome of this paper can be used in communities which are connected to the main network through a tie line, in order to preserve the network integrity after disconnecting the tie line, by suitable load shedding and load restoration.

The structure of this paper is as follows: In Section 1 the introduction of this paper is given. Section 2 discusses the theory of the suggested procedure. Section 3 presents the algorithm of the presented method. In Section IV a case study is analyzed. The results of the simulation of the case study demonstrate the potential of the method for maintaining the region after disconnecting from the main grid. In Section V the implication issues are considered. Finally, Section VI concludes the outstanding aspects of the proposed methods.

## 2. ELECTROMECHANICAL EQUATIONS CONSIDERING VOLTAGE CONTROL AND DROOP CHARACTERISTIC OF THE GENERATORS

Consider a region consists of  $m$  generators, the electromechanical equation for the generators can be written as

$$\frac{J_k}{w_s} \frac{dw_k}{dt} = P_{m,k} - P_{e,k} - P_{D,k} \quad (p.u.) \quad (1)$$
$$k = 1, 2, \dots, m$$

where

$w_s$  = Synchronous speed (rad / Sec).

$J_k$  = Moment of inertia of Generator  $k$ .

$w_k$  = Electrical speed of the rotor of Generator  $k$ .

$P_{e,k}$  = Electric power produced by Generator  $k$ .

$P_{m,k}$  = Mechanical power of Generator  $k$ .

$P_{D,k}$  = Damping power of Generator  $k$ .

The electrical power produced by the each generator can be found using the reduction matrix method as given in [8]. The complex produced power for each generator can be found from

$$S_g = \text{Diag} \{V_g I_g^*\} = [S_I \quad L \quad S_k \quad L \quad S_m] \quad (2)$$

$I_g$  = The injected generator bus current vector.

$V_g$  = The generator voltage bus vector

Therefore, the electrical power needed,  $P_{e,k}$ , needed in Equation (1) is the real part of  $S_k$  as

$$P_{e,k} = \text{Real}\{S_{e,k}\} \quad (3)$$

The damping power for Generator  $k$  can be obtained from

$$P_{D,k} = D_k W_k \quad k = I, L, m \quad (4)$$

where

$D_k$  = Damping coefficient of Generator  $k$ .

The produced electric power of the generators are calculated from the power flow equation at each time step of the differential equations being solved. Also the differential equation corresponds to excitation can be expressed as

$$\frac{dE_k}{dt} = \frac{K_{E,k}}{T_{E,k}} (V_{t,k} - V_{ref,k}) - \frac{E_k}{T_{E,k}} \quad (5)$$

$k = I, L, m$

where

$E_k$  = Excitation voltage of Generator  $k$ .

$T_{E,k}$  = Field time constant of Generator  $k$ .

$K_{E,k}$  = Field gain of Generator  $k$ .

$V_{t,k}$  = Voltage terminal of Generator  $k$ .

$V_{ref,k}$  = Voltage reference of Generator  $k$ .

When the region is connected, the input mechanical power of the generators is equal to power associated with the output signal of the governor. However, when the region becomes an island, i.e. is disconnected from the network, it goes into frequency control mode. In this situation the input mechanical power of the Generator  $k$ ,  $P_{m,k}$ , is considered to be related to the power associated with the governor of Generator  $K$ ,  $P_{gov,k}$ , by a first order differential equation as:

$$\frac{dP_{m,k}}{dt} = \frac{P_{gov,k} - P_{m,k}}{T_{g,k}} \quad k = I, L, m \quad (6)$$

where

$P_{gov,k}$  = The power associated with the output signal of the governor for Generator  $K$ .

$P_{m,k}$  = Input mechanical power of the Generator  $k$

$T_{g,k}$  = Governor time constant of Generator  $K$ .

The relationship between the output power associated with the output signal of the governor and frequency is called droop characteristic and shown in Figure 1. In this figure, the horizontal axis shows the output power associated with the output signal of the governor of Generator  $k$  or the mechanical power input of Generator  $k$ ,  $P_{m,k}$ , and the horizontal axis represents the frequency deviation from the nominal frequency.

Since according to Equation (6) and Figure (1), for Generator  $K$  the output power associated with the output signal of the governor,  $P_{gov,k}$ , is related to the frequency,  $f_k$ , the output mechanical power associated with the output signal of the governor,  $P_{gov,k}$ , needs to be expressed in terms of frequency as

$$P_{gov,k} = \frac{R_k P_{max,k} + f_k}{R_k} \quad k = I, L, m \quad (7)$$

where

$f_k$  = The frequency deviation from nominal frequency, i.e. 50 HZ.

$R_k$  = Regulation constant for Generator  $k$

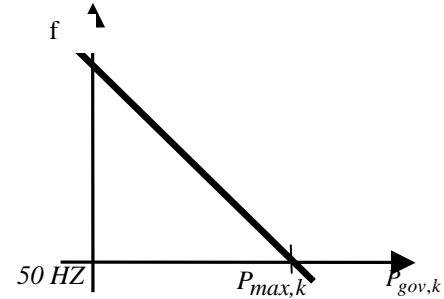


Figure 1: The droop characteristic of Generator  $K$  [9]

In the islanding mode of operation of the region the output power of the governor is determined by Equation (7). Note that the limitation of the maximum power for the generators also needs to be applied to the equations. To take into account this limitation the following constraint is considered in solving the differential equations.

$$\begin{cases} P_{gov,k} = \frac{R_k P_{max,k} + f_k}{R_k} & \text{if } f_k > 0 \\ P_{gov,k} = P_{max,k} & \text{if } f_k \leq 0 \end{cases} \quad (8)$$

$k = I, L, m$

In this situation, when the region is disconnected from the main network the state variables corresponding to Equations (1)-(6) is

$$X = [d_I \ w_I \ E_I \ P_{m,I} \ L \ d_m \ w_m \ E_m \ P_{m,m}] \quad (9)$$

When the region is connected to the network, the power to the generators is not influenced by the system frequency. Therefore, the mechanical powers in Equation (9),  $P_{m,I}, L, P_{m,m}$ , are not considered in this situation.

### 3. LOAD SHEDDING AND RESTORATION PROCEDURES AFTER DISCONNECTING THE TIE-LINE

#### 3.1. LOAD SHEDDING PROCEDURE

Consider the case that the region is connected to the main network through a tie line. The region imports electrical power from the main network. If the circuit breaker of the tie-line is tripped, the region in the network then becomes separated from the network. As stated previously, in our

study there is no communication between the generators and the frequency of the network is the only common information for control of the generators. Also, the information of droop characteristic of all generators is available to each generator.

After disconnecting the region from the main network, the region is referred to as the electrical island. As the load is typically less than the generation in the island at the time of separation, the frequency in the island starts to drop. According to the shedding procedure the loads are shed until the frequency drop is stopped and starts to rise. The shedding procedure is based on a predefined shedding policy. Any policy for load shedding such as prioritized load can be considered in the shedding procedure.

Considering the case that the total rated power of the generators in the island can meet the total load in the island, eventually the frequency of the island becomes stable and the region keeps its integrity by initially removing some of the loads in the region and gradually restoring them. Figure 2 shows the flowchart of shedding process for shedable load  $i$ . The frequencies  $f_{island}$  and  $f_{shed_i}$  are the island frequency and shedding frequency of shedable load  $i$ . Although in the flowchart of shedding process shown in Figure 2 the shedding is performed based on the frequency, the rate of frequency changes can be used as another alternative tool in the shedding process. The ordering in load shedding (if any) might be coming from a shedding policy set by the utility in the island.

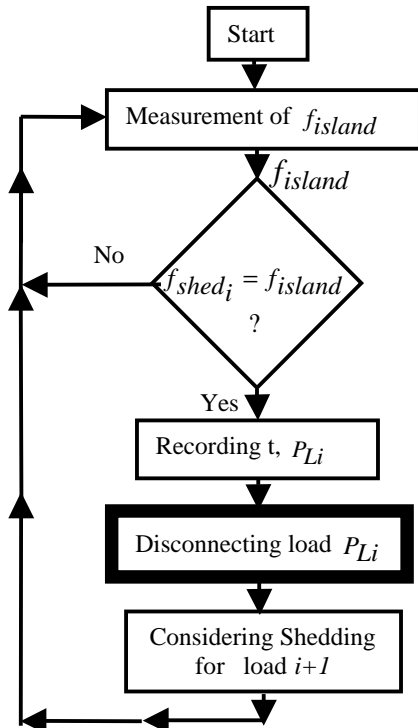


Figure 2: Flowchart of shedding procedure.

When the frequency stabilised, i.e. there is no more reduction in the island frequency, then due to predefined droop characteristic of each generators, the produced power of the generators increase. Thus, the frequency rises

### 3.2. LOAD RESTORATION PROCEDURE

In the restoration procedure we consider the case that the information of the droop characteristic of all of the generators are provided for each individual generator. The flowchart of the restoration procedure is shown in Figure 3.

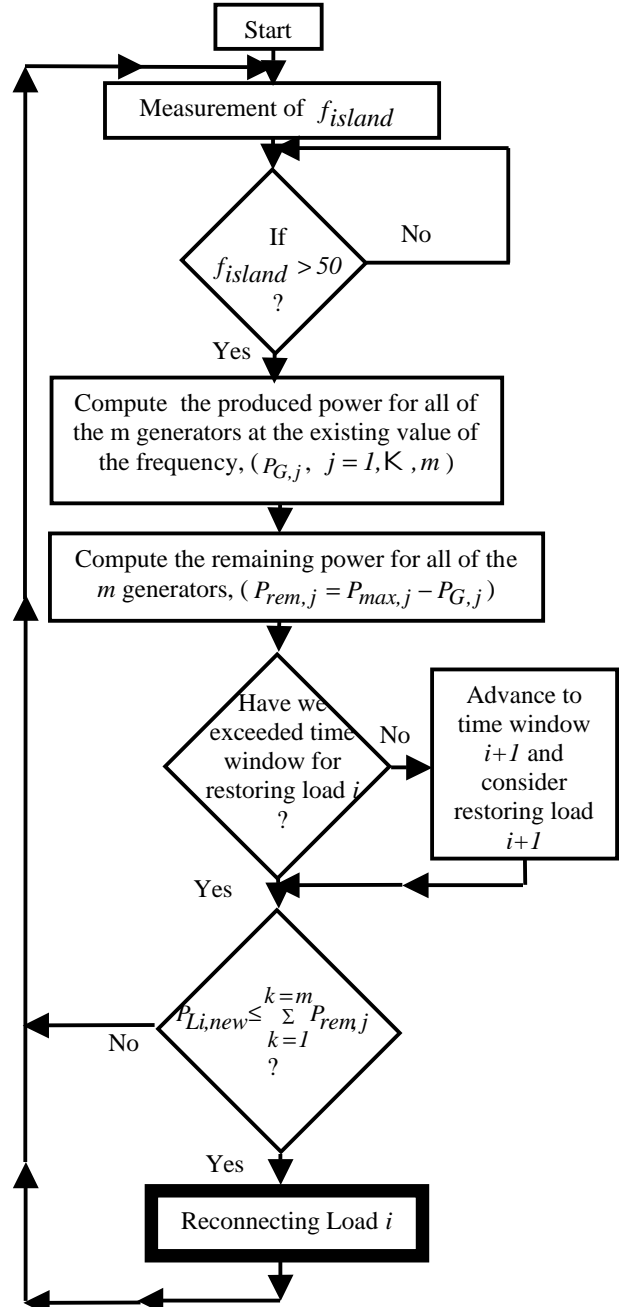


Figure 3: The flowchart for the restoration procedure

In the proposed algorithm for restoration process, the droop characteristic of the generators need to be adjusted so that the rated load is supplied at the frequency which is more than 50 HZ. The restoration process comes to effect when the frequency goes more than 50 HZ. In the simulation, at each time step of the restoration process, the produced power of each generator is computed according to the frequency of the island at that step using the droop characteristic of each generator. Then, for each generator the produced power is subtracted from the maximum power of the generator and the result is referred as the remaining power,  $P_{m,i}$ , for that generator. The restoration of a specific load will be performed if the

power of the of the incoming load,  $P_L$ , is less than or equal to the total remaining of the generators. In the real power system the droop characteristic of the generators are to be chosen to be similar or, alternatively, for each load the droop characteristic of all of the generators are provided. Therefore the loads can asses that which time suits it to reconnect to the load. Also the restoration policy may incorporate the prioritized loads in restoration.

## 4. CASE STUDY

### 4.1. SYSTEM DESCRIPTION

In order to validate the proposed method in surviving the region after disconnecting from the main network, the network shown in Figure 4, is studied. As shown in this figure, the region consists of two generators and two shedable loads. The shedable loads can be shed gradually as the fraction of the full load. The region is connected to the main network. The main network is treated as an infinite bus for the region.

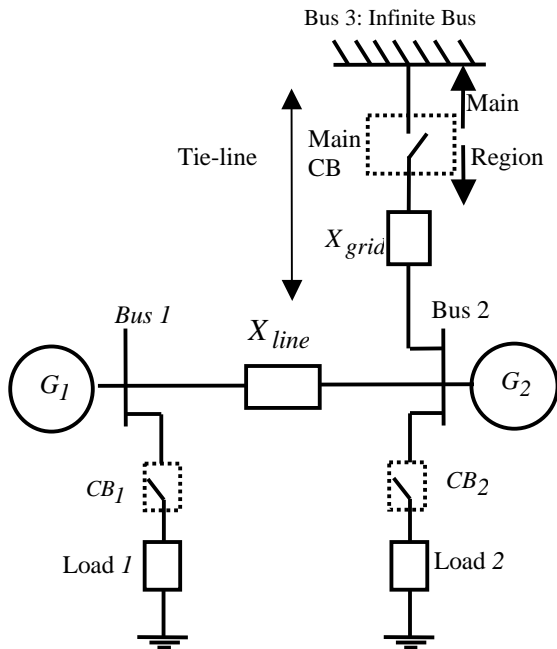


Figure 4: A region connected to the main network via tie-line

For the network shown in Figure 4, the system is studied before and after disconnecting the region from the main network. The parameters for the test system are given in the appendix of this paper.

For the situation before disconnecting the network from the main network in Figure 4, the electromechanical equations are written according to Equation (1).

For the test system, the differential equations associated with the generator fields are determined according to Equation (5).

Equations (1)-(5) are used to simulate the situation the test system before disconnecting the region from the main network. In this situation, the state variables for the test system are

$$X = [d_1 \quad w_1 \quad E_1 \quad d_2 \quad w_2 \quad E_2] \quad (10)$$

where

$d_1$  and  $d_2$  = Rotor angles of Generator 1 and 2, respectively.

$w_1$  and  $w_2$  = Speed of Generator 1 and 2, respectively in  $rad / Sec$ .

$E_1$  and  $E_2$  = Excitation voltage of Generator 1 and 2, respectively

When the region is disconnected from the main network, the governors of the generators come to effect. The differential equations corresponding to the governors of the generators in the test system are described by Equation (6).

According to Equation (7), the droop characteristic of the generators for the test system can be obtained from

$$P_{gov,1} = \frac{R_1 P_{max,1} + f_2}{R_1} \quad (11)$$

$$P_{gov,2} = \frac{R_2 P_{max,2} + f_2}{R_2} \quad (12)$$

Also as expressed in Equation (8), whenever according to Equation (7) and (8), the mechanical power goes beyond the maximum power, the value of the mechanical power is set at the maximum power.

### 4.2. LOAD SHEDDING PROCESS

In this section, only the load shedding is considered and In the shedding process of the test study, the loads are considered to be shed gradually at different shedding frequency. The shedding frequencies for Load 1 and Load 2 are chosen as

$$f_{shed1} = [0.4 \quad 0.9 \quad 1.6 \quad 1.8 \quad 2] \text{ (Hz)} \quad (13)$$

$$f_{shed2} = [0.5 \quad 0.95 \quad 1.4 \quad 1.8 \quad 2.1] \text{ (Hz)} \quad (14)$$

According to frequencies values given in Equations (13) and (14), the shedding pattern for the two loads are

$$Y_{shed1} = [0.9 \quad 0.6 \quad 0.4 \quad 0.1 \quad 0] Y_{load1} \quad (15)$$

$$Y_{shed2} = [0.8 \quad 0.7 \quad 0.55 \quad 0.35 \quad 0] Y_{load2} \quad (16)$$

For example if the frequency drops and lies in the range of 0.4 to 0.9 HZ below 50 HZ, the admittance of Load 1 reduces to 90% of its original value. Also Load 1 is completely shed if the frequency falls below 48HZ and Load 2 is disconnected from the network if the frequency becomes less than the 47.9 HZ.

The region shown in Figure 4 initially is connected to the main network and imports electrical power via tie-line. At  $t=2 \text{ Sec.}$ , the circuit breaker of the tie-line operates and the region is disconnected from the main network. Figure 5 shows the produced power of the generators and imported power from the main network.

After the disconnection the tie-line, the frequency and the loads are shed stepwise. The frequency deviation from 50HZ are illustrated in Figure 6. It should be mentioned that the frequency in a real network is the same throughout the network. However, in the simulation, according to Equation (10), speed of the generators are two distinct variables. For this reason the frequency of the generators are plotted separately in Figure 6.

The value of loads during the shedding process are shown in Figure 7. The vertical axis show the value of steps of Load 1 and Load 2 at instant of shedding. For example, at  $t=2.07 \text{ Sec.}$ , The admittance of Load 1 is reduced by 10%. The first bar in two plots in Figure 7 represents the admittances of the loads before the shedding process.

The electric power of Load 1 and 2 depicted in Figure 8. The step changes in the load powers in Figure 8 are corresponding the step changes of the load admittances.

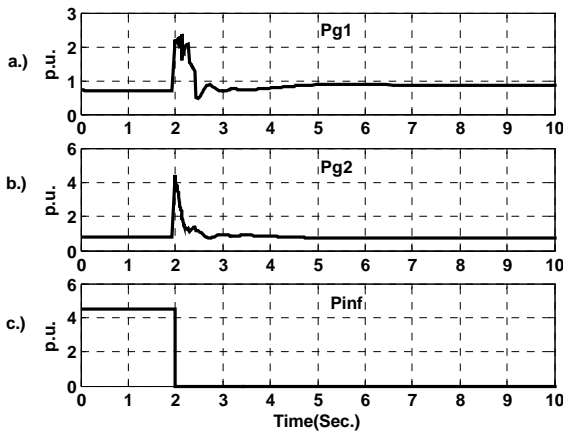


Figure 5: a.) Supplied power of Generator 1, b.) Supplied power of Generator 2, c.) The power supplied by the infinite bus to the region

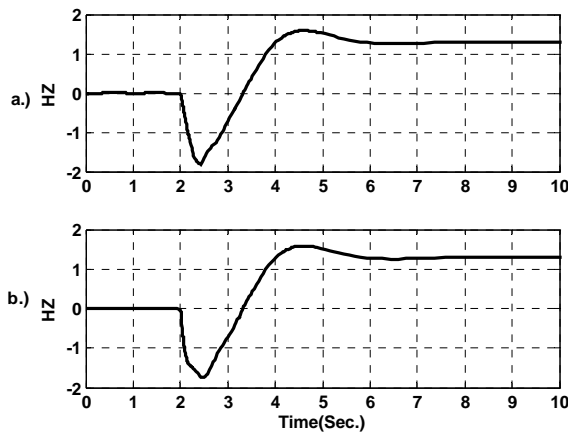


Figure 6: The frequency deviation during shedding process for a.) Generator 1, b.) Generator 2, during the shedding process

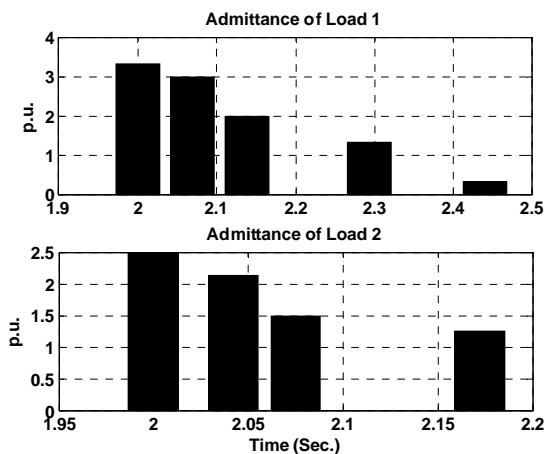


Figure 7: Different values for Load 1 and Load 2 during the shedding process

From the time that the region becomes separated from the main network, the generators go the frequency control mode. Figure 9 shows the power associated with governor output signal ( $P_{gov1}$ ) as well as the mechanical turbine of Generator 1. The same characteristic for Generator 2 is illustrated in Figure 10.

As previously explained, in the simulation the voltage control block is considered according to Equation (5). The versions of the excitation voltage of the generators are shown in Figure 11.

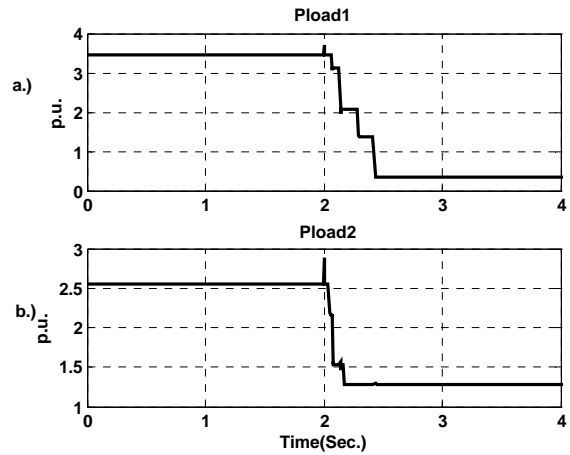


Figure 8: a.) Power of Load 1, b.) Power of Load 2, during the shedding process

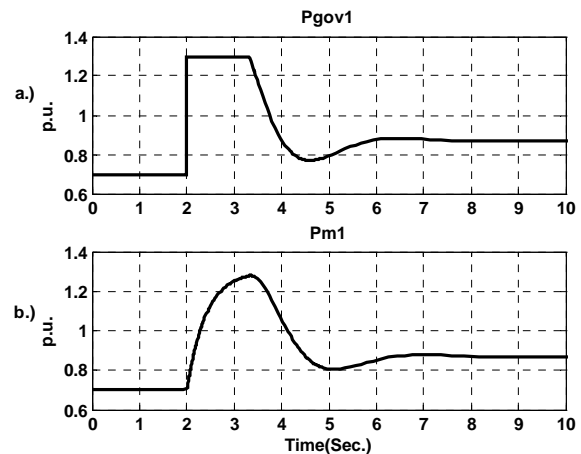


Figure 9: a.) The output power associated with governor output signal, b.) The mechanical turbine, for Generator 1 during the shedding process

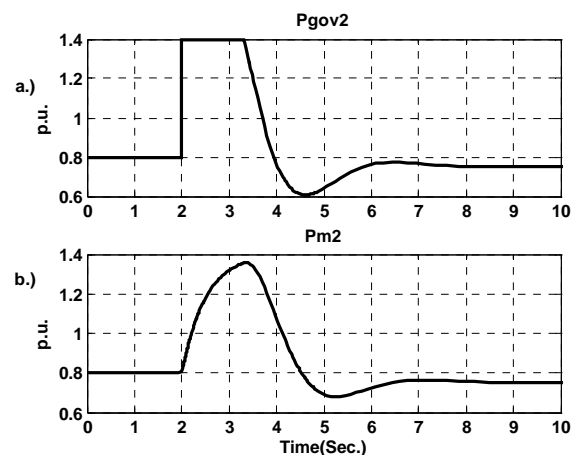


Figure 10: a.) The output power associated with governor output signal, b.) The mechanical turbine, for Generator 2 during shedding process

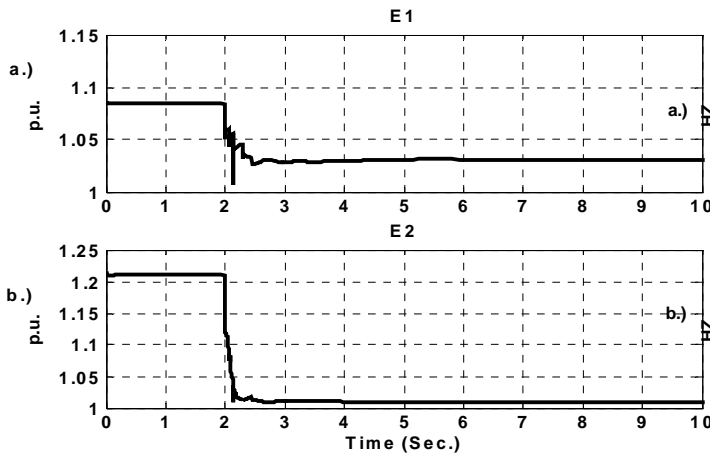


Figure 11: The excitation voltage a.) for generator 1, b.) for generator 2

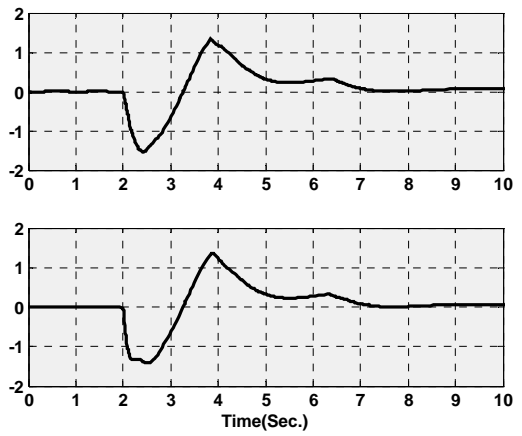


Figure 13: The frequency deviation during shedding and restoration processes for a.) Generator 1, b.) Generator 2

### 4.3. RESTORATION PROCESS

In this section both load shedding and load restoration for the test study are studied. The parameters of the system are as before and given in the Appendix except the maximum power of the generators. To demonstrate the capability of the proposed method in the load restoration the maximum power for the generators are chosen as

$$P_{max1} = 2.3 \text{ and } P_{max2} = 2.4 \text{ p.u.}$$

In the simulation, after performing the load shedding, the frequency rises according to droop characteristic of the generators. When the frequency goes above 50 Hz, the restoration process according to the flowchart of Figure 3 comes to effect. The admittance of the load is allowed to be increased if the two generators are capable to supply the new value for the load considering the maximum power of each generator (see the flowchart of Figure 3).

The selected duration of the time window mentioned in the flowchart of Figure 3 is 2 Sec. Figure 12 shows the shedding and restoration processes for Load 1 and Load 2 of the test system. As shown in Figure 12, for Load 1, firstly two steps of the load are shed and then one step is restored. For Load 2, initially three steps are shed, then one step restored.

According to Figure 13, after load shedding and load restoration, the frequency becomes stable and the system keeps operating after disconnecting from the main network. Also as Figure 13 shows that as the loads are restored, the frequency drops.

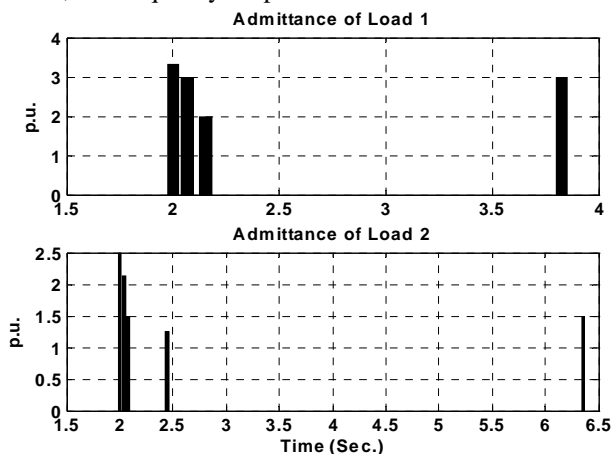


Figure 12: Different values for Load 1 and Load 2 during the shedding and restoration processes

The produced powers of the generators are shown in Figure 14 and the load powers are shown in Figure 15. As Figures 14 and 15 indicate by restoring loads the output power of the generators as well as load powers increase.

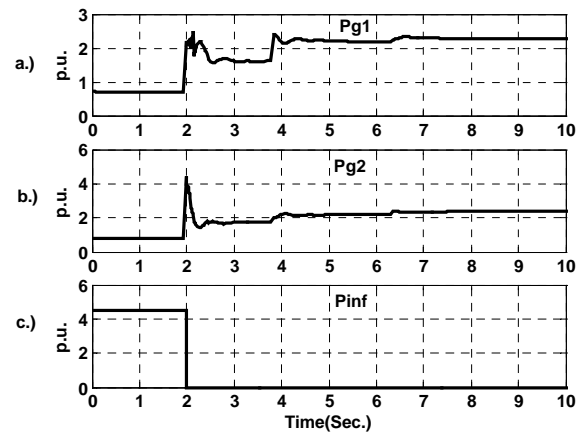


Figure 14: a.) Supplied power of Generator 1, b.) Supplied power of Generator 2, c.) The power supplied by the infinite bus to the region, during the shedding and restoration processes

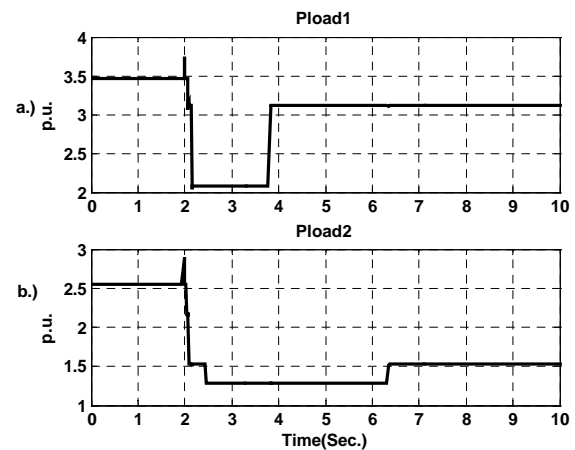


Figure 15: a) Power of Load 1, b.) Power of Load 2, during the shedding and restoration processes

According to the suggested method and as Figures 12-15 indicate, after disconnecting the region from the main network, some loads are shed to save the region from blackout. Also, after stabilization some loads are restored.

## 5. IMPLICATION ISSUE

The suggested method examined in this paper is based on this issue that there is no communication between the generators. The island frequency and knowledge of the droop characteristic provide the tools. However, the following issues need to be considered for completeness of control:

- The ordering for load restoration requires having the precise time of synchronisation.
- In the suggested method, we consider the case that a perfect identification of the time of the separation the region from the network is available.
- It is assumed the after the disconnection of the region from the network, the generators are able to detect the need to go to frequency-control mode from power control mode.

## 6. CONCLUSION

In this paper a method is presented for survival of an electrical island when it becomes separated from the main network. The method has two stages. In the first stage a load shedding stage occurs. The second stage includes a restoration process. Load restoration depends on the droop characteristic of the generators and maximum power capability of the generators. The proposed method is based on zero communication between the generators and loads. In this method the available information are island frequency and the droop characteristic of the generators. In this paper after presenting the flowchart for load shedding and load restoration, the suggested method is simulated on a test system. Results of the simulation indicate that using this method successfully prevents the island from blackout when it becomes separated from the network without explicit communication between loads and generators.

## 7. ACKNOWLEDGEMENTS

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## APPENDIX

The specifications of test power system of Section 5.8 are as follows:

$$\begin{aligned} J_1 &= 0.0191 & J_2 &= 0.0159 \\ D_1 &= 0.2 & D_2 &= 0.25 \\ R_1 &= 0.06 & R_2 &= 0.04 \\ T_{g,1} &= 0.4 \text{ Sec.} & T_{g,2} &= 0.5 \text{ Sec.} \\ K_{E,1} &= 100 & K_{E,2} &= 110 \\ T_{E,1} &= 0.02 & T_{E,2} &= 0.03 \\ X_{line} &= 0.15 j & X_{grid} &= 0.1 j \\ P_{max,1} &= 1.3 & P_{max,2} &= 1.4 \\ Z_{load1} &= 0.3 & Z_{load2} &= 0.4 \\ V_{ref,1} &= 1.03 & V_{ref,2} &= 1.02 \end{aligned}$$

$$X'_{d1} = 0.1 \text{ (Direct axis transient reactance of Gen. 1)}$$

$$X'_{d2} = 0.12 \text{ (Direct axis transient reactance of Gen. 2)}$$

All of the above parameters except time constants in *p.u.* and the synchronous frequency is 50 HZ.