

# Load Shedding Application within a Microgrid to Assure Its Dynamic Performance during Its Transition to the Islanded Mode of Operation

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## ABSTRACT

This article presents the simulation results and analysis related to the response of the generators within a microgrid towards an accidental overload condition that will require some load shedding action. A microgrid overload can occur due to various reasons ranging from poor load schedule, inadequate switching of circuits within the microgrid, outage of one or more generators inside the microgrid, illegal load connections by some low voltage consumers, etc. It was observed that among the main factors that determine the survival of the microgrid during its transition from the grid connected mode to the islanded mode of operation are the size and type of the load connected (passive or dynamic load) as well as the length of time during which the unexpected load is connected. Models of a speed and voltage regulators of a diesel generator, and important for coping with the overload conditions are provided in the paper. The novelty of the work lies in the load shedding simulation and analysis of the specific generators studied herein, regarding that in many countries the microgrid technology is seen as an important alternative towards the ever increasing load demand and also to assist the system during periods of blackout.

**Keywords:** Distributed Generation; Islanded Operation Mode; Load Shedding; Microgrid Systems

## 1. Introduction

At present, the establishment of microgrid systems is regarded by the power industry as one of the alternatives to not only keep running critical loads but also provide electricity to some regular consumers during periods of prolonged interruptions (e.g. blackouts). Microgrid systems are the compelled choice in remote areas where it is difficult to provide power through the power system. The microgrid concept is not new; actually, in the early days of the power industry this was the kind of system established in the urban and industrial areas. The interconnection of systems to strengthen and form the network came years later. This was done to offer the system a high level of safety regarding possible faults; thus, cope with stability issues aside of allowing the surplus generation capacity in one area to be used elsewhere in the system.

Ironically, this kind of system networking may also lead to some major interruptions (due to cascading effect) like those that affected central, south and southeastern

Brazil and all Paraguay in 2009, the northeastern part of the USA in 2003, and all Italy in 2003. Also, nearly 100 million people in Indonesia were affected by a huge blackout in 2005. The last major blackout occurred in India in 2012 leaving virtually inoperative in the Northern, Eastern and Northeast part of the country. In the aftermath of these undesired events nearly all the affected systems set up independently a common action, to seek for some alternatives capable to diminish their impact among which the establishment of microgrid systems was also pointed out.

One of the key features of a microgrid is its ability to separate itself from the distribution utility (e.g. during unscheduled periods of interruption) in order to continue feeding its own islanded portion. This is not a simple task though, especially when taking into account the compelled operational procedures and protocols to be followed.

Another outstanding characteristic of a microgrid is that, provided an agreement with the grid, it can supply its surplus generation to the utility, for example, during

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peak periods of demand or whenever the microgrid has excess capacity.

Microgrid systems, when properly designed, have the ability to separate from the distribution utility, for example, during disturbance or blackout periods experienced by the utility. This gives them the possibility to continue feeding their own islanded portion. Additionally, provided an agreement with the distribution utility, they can supply their surplus generation whenever they have excess capacity. This is particularly attractive for periods when the utility faces peak periods of demand. Nonetheless, it can occur that during the transition from the grid connected mode to the islanded mode of operation, an excessive load (larger than the microgrid can uphold) could be connected to the microgrid.

This overloading condition can occur due to various reasons, namely: poor load schedule, inadequate switching of circuits within the microgrid, an upstream tripping of the utility circuit breaker that leaves part of its load connected to the microgrid, illegal load connections by some low voltage consumers, etc. Under this condition, the most common way to save the microgrid from a complete collapse is to shed part of the load connected. This action can help the fading generator to become stable again ensuring its safe operation.

Some critics say that the application of load shedding at specific times during the 2003 major blackout in North America could have prevented the cascading outages that came after the initial tripping event.

Several interesting references addressing the load shedding issue in large systems were found. There may also be some other references having the same merit; however, due to space restrictions of this article it will not be possible to include them all.

Reference [1], for example, provides a comprehensive coverage on the load shedding issue, load restoration and generator protection schemes using underfrequency relays during abnormal frequency conditions. In [2], an underfrequency protection program developed for a certain region in North America is presented. The program reportedly optimizes the system wide load shed schedule, also checking up its coordination with a steam turbine-generator underfrequency protection scheme. In [3], a method for determining the maximum probable rates at which a power system frequency will decay, following a disturbance, is presented. Such an analysis is chiefly directed to provide underfrequency protection for nuclear power plants. Reference [4], presents a summary on System Protection and Voltage Stability prepared by the IEEE Power System Relaying Committee. It describes the risk and mechanism of voltage collapse as well as suggests some operation, system upgrades and protection solutions to avoid such a condition.

In [5] the effect of the reduced frequency upon the ca-

capacity of a power plant, with special regard to cases with deficiency of generation, is presented. It is stated that on systems with a high percentage of motor load (such as pumping), a combination of frequency and voltage reduction may secure maximum load relief during an emergency. In [6-9], some methods dealing with underfrequency load shedding, so as to avoid voltage instability and its further collapse, are presented.

In [10] an optimal load shedding algorithm based on an economic criterion is developed. In [11], a strategy to shed an optimal number of loads in an islanded distribution system, using factors like the rate of change of frequency (RoCoF) and the customers' willingness to pay during periods of outage to stabilize its frequency, is presented.

Finally, in [12] a scheme that combines frequency and voltage changes to shed loads is proposed. The premise behind this scheme is that in the last years, power systems have changed and yet no corresponding modification of the underfrequency load shedding schemes was made; thus, the load shedding procedure would still be based on the disconnection of pre-selected loads.

As can be seen, most of the above reviewed load shedding methods and strategies are directed to large systems, hence the need to develop a study on the excessive overloading effects on microgrid generators. The article presents the main control components of a gen set and the various situations the microgrid generators can face during the transition from the grid connected to the islanded mode of operation.

The microgrid current status and some of the challenges presently encountered by the microgrid technology, are presented in [13]. In [14,15] a microgrid islanding condition following a fault and its respective stability behaviour are investigated. The load shedding alternative is applied once the system frequency starts to decay from its nominal operative value (50 or 60 Hz).

According to [16,17], the two load shedding methods widely used are:

1) Traditional frequency drops with load percentage shed. Typically, the load shedding scheme can be done in 3 (and up to 6) steps [16]. For example, in a three-step method, the percentage of load shed would be:

Step	f (Hz)	(%) of load
1	59.3	10
2	58.9	15
3	58.5	as required to avoid going below 58.2 Hz

2) Use of the rate of change of frequency (RoCoF) and load percentage sheds. It evaluates the speed at which the frequency ( $df/dt$ ) is declining. This enables characterizing the kind of contingency occurring in the system at vari-

ous instants, thus, provides the system a most adequate load shedding scheme [17]. For example, regarding the above frequency drop of 59.3 Hz, the  $df/dt$  could be set at:

- 59.3 Hz .....  $df/dt = 0.4 \text{ Hz/s}$  .... 10% of total load.
- 59.3 Hz .....  $df/dt = 1.0 \text{ Hz/s}$  .... 25% of total load.
- 59.3 Hz .....  $df/dt = 2.0 \text{ Hz/s}$  .... 35% of total load.

The above under-frequency control methods are commonly used by many distribution utilities. In the context of this paper, the entire load exceeding the normal power demand of the microgrid internal generation will be shed. This is done considering the simulation response of the generators in returning to the pre-overload condition. Also, the inherent differences existing between the grid and a microgrid should be considered. In the latter case, for example, the inertia of the generation sources is much smaller.

Generally, gen-sets like the one considered here have no overloading capability. Wind generators and small hydro generators may admit little overload (up to 10%). Nevertheless, a brief analysis on what would be the percentage of load to be shed, if the above methods were also used, will be included whenever appropriate.

## 2. Microgrid Load Shedding Application

The transition from a grid-connected to an islanded mode of operation of a microgrid can occur due to reasons like the presence of faults in the system, or due to some pre-planned conditions like the system (grid) maint-

nance, energy costs, etc. During such a transition the power control of the microgrid generators must act quickly as they start controlling the frequency of the islanded section.

Whenever power in the network is lost, the microgrid generators assigned to provide power to the intentionally islanded portion should be able to pick up and feed the load of the islanded system after the switch at the Point of Common Coupling (PCC) has opened. The generation sources herein referred can be any of the sources cited by the IEEE std. 1547 [18]: PV arrays, wind turbines, fuel cells, microturbines, conventional diesel, gas-fired turbines, and energy storage technologies.

The microgrid system to be analyzed is connected to the utility through a circuit-breaker (CB), in series with a 6 MVA, 13.8/2.4 kV transformer, as depicted in **Figure 1**. The energy sources in the considered microgrid are: a synchronous generator driven by a diesel engine (connected to PCC through CB-1); a wind turbine driving a synchronous generator (connected to PCC through CB-3) and another small synchronous machine which could represent a small hydro-generator (SHG) connected to the PCC through CB-2. No PV array sources (solar panels) or sources requiring energy storage elements were considered because the primary focus of this research is to analyze the dynamic behaviour of the considered sources. Also, the machine equations are not presented here as they can be found in the available literature dealing with electric machines.

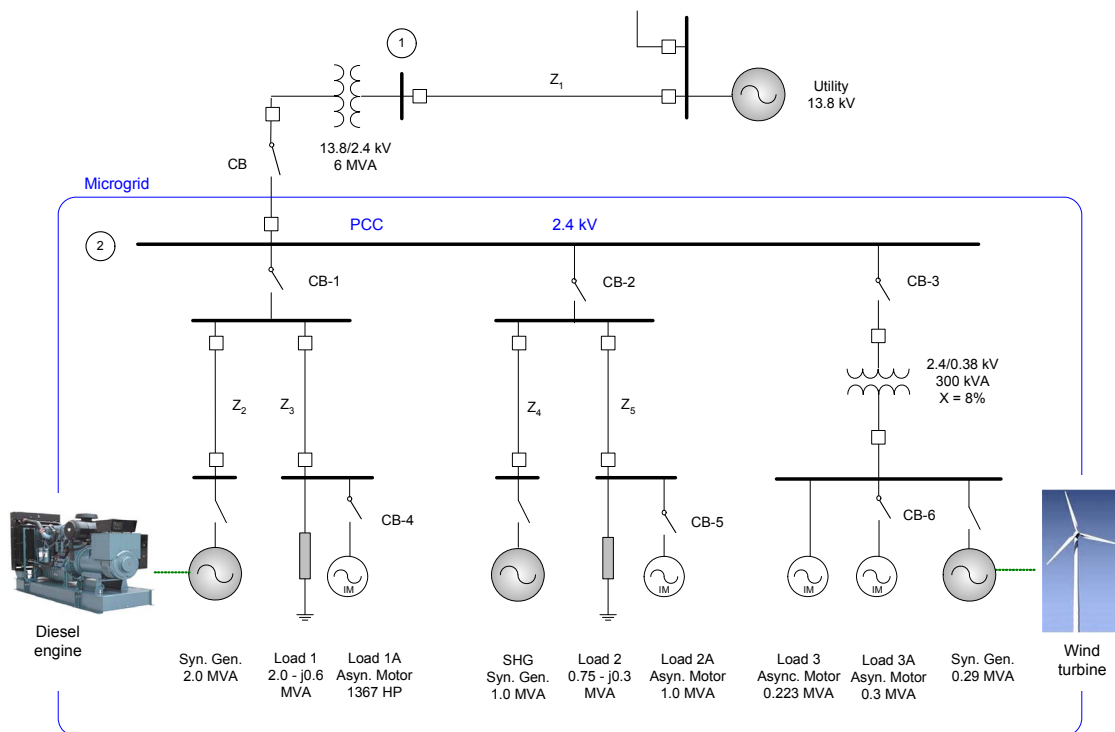


Figure 1. Microgrid system used in the simulations.

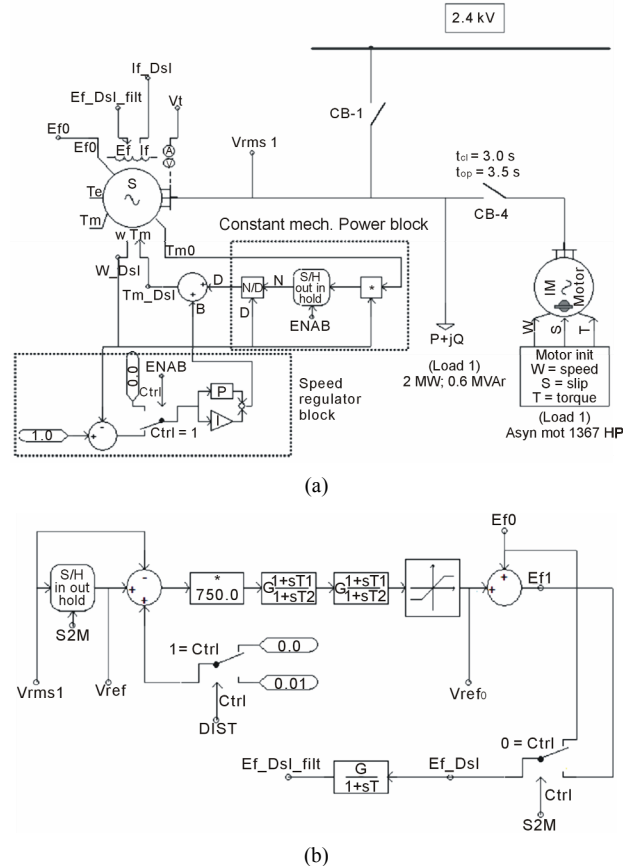
The wind generator is connected to the microgrid through a 2.4/0.38 kV transformer. In practice, due to technical and economic reasons, most of the sources used in wind power schemes are asynchronous generators. One of the main reasons has to do with its ability to operate at speeds different from the synchronous speed. However, in this study, a synchronous generator was chosen due to its less dependency from an external source for providing reactive power. A Doubly Fed Induction Generator (DFIG) was also placed instead of the wind (synchronous) generator; its response was comparable to the synchronous generator used herein.

The loads fed by each generator, as well as the extra loads (equivalent asynchronous motors) that simulate the overloading condition (*Load 1A*, *Load 2A* and *Load 3A*) are also shown in **Figure 1**. These extra loads are connected to their respective generator through CB-4, CB-5 and CB-6. *Load 1* and *Load 2* were specified as constant power loads. The normal load connected to the wind generator (*Load 3*) is a dynamic load (equivalent asynchronous motor). The complete system was implemented in the EMTDC/PSCAD<sup>®</sup> program [19]. Some components, like the electrical generators and circuit breakers were taken from the software library, while others, like the diesel generator speed and voltage regulators, etc., were independently built and defined.

The sequence of the load shedding procedure is as follows: initially, all loads are primarily being fed by the utility when, due to any reason (e.g. a three-phase fault), the circuit-breaker (CB) is open. At this moment all three generators start running and taking up their respective loads. It is assumed that along with CB the other circuit breakers (*i.e.* CB-1, CB-2 and CB-3) also trigger with the fault. This way, it will be avoided the condition of any of the generators from being carried away by another generator. This condition is critical in microgrids containing several sources; otherwise, the whole microgrid system can be jeopardized by the loss of synchronism among them. Synchronization of fully-loaded generators is commonly unachievable, hence the need to open CB-1, CB-2 and CB-3. But that is an issue that for now is put aside.

## 2.1. Diesel Generator Overloading

Among the control systems implemented on this generator are: a basic speed regulator, a constant mechanical power regulator (**Figure 2(a)**) and a voltage regulator (**Figure 2(b)**). As it will be shown later, a reasonably robust voltage and speed regulator may be useful in helping the machine cope with faults on the system. Most of the synchronous generator parameters like the direct and quadrature reactances as well as the transient and subtransient time constants ( $X_q$ ,  $T''_{do}$ ,  $X''_q$ ,  $T''_{qo}$ , etc.) were estimated according to [20]. The machine starts as an



**Figure 2. (a) Synchronous (diesel) generator model; (b) Voltage regulator.**

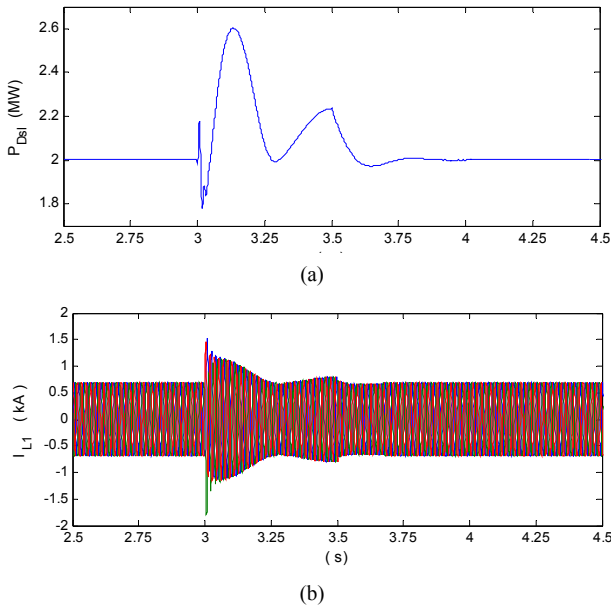
ideal source ( $t = 0.0$  s) until it reaches its steady-state condition. At  $t = 0.5$  s the model enables the machine to pass from an ideal source to a non ideal machine, simultaneously the voltage regulator control is inserted in to the generator. No cylinder misfiring condition was simulated.

At  $t = 2.0$  s, once the initialization transient reaches a stable condition, the dynamic model of the machine is enabled. From this moment on, the machine electromechanical equations start driving the generator, enabling the variation of the speed and mechanical torque. Initially, the diesel gen-set is feeding a linear load ( $L_1 = 2.0 + j0.6$  MVA) when at  $t = 3.0$  s an equivalent induction motor representing 50% of excess load ( $L_{1A} = 1367$  Hp) is connected. The extra load (*Load 1A*) is switched off after 500 ms. It can be seen that at first the generator intends to take up this extra load (see  $P_{Dsl}$  in **Figure 3(a)** and also the stator current  $I_{L1}$  in **Figure 3(b)**) though failing in its attempt. The instant the load shed occurs (opening of CB-4 at  $t = 3.5$  s) relieves the machine which quickly returns to its previous loading condition. The P-I (proportional-integral) constants define how quickly the machine will return to the pre-overloading condition.

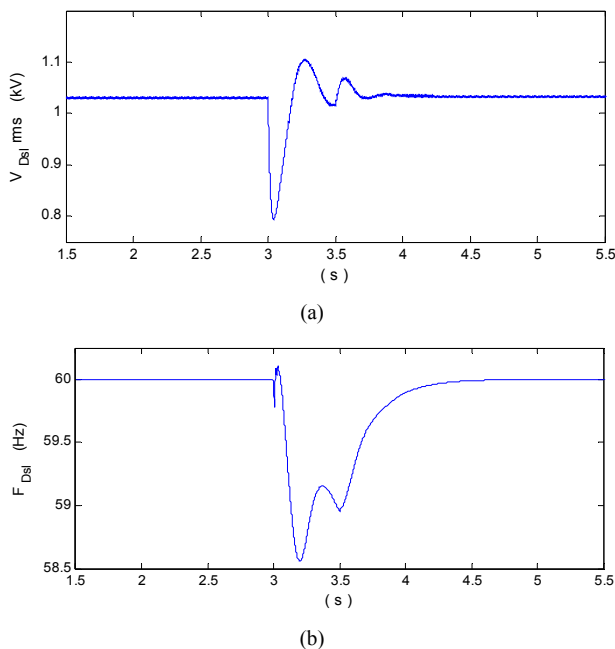
The terminal voltage ( $V_{Dsl,rms}$ ) shown in **Figure 4(a)**

drops instantly, upon which, following a few oscillations the voltage regulator carries it back to its previous operative value (1.03 pu). The gen-set frequency ( $F_{Dsl}$ ) shown in **Figure 4(b)** reaches a minimum value of 58.6 Hz. If the conventional load shedding strategies were to be applied (see Section 1), the amount of load to be removed would be the highest specified.

For example, according to [16], the percentage of load to be shed, regarding the minimum value of 58.6 Hz,



**Figure 3. (a) Diesel generator power; (b) Current at the stator.**



**Figure 4. (a) Diesel generator terminal voltage; (b) Frequency.**

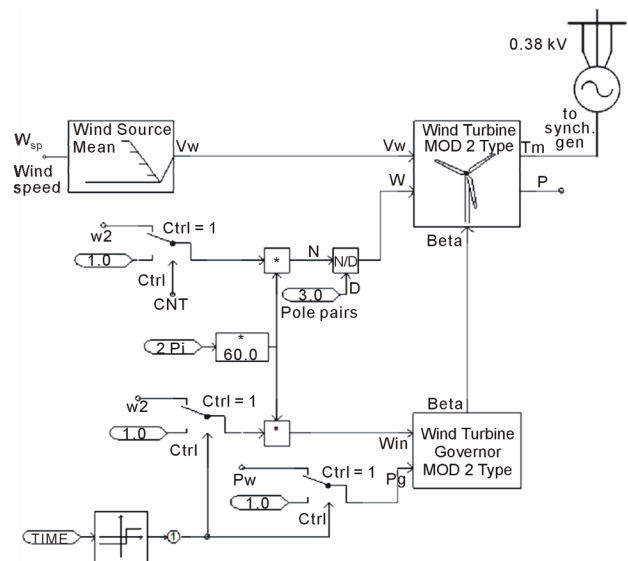
would be above 15% (*i.e.* as required to avoid falling further the frequency). Now, according to [17], the percentage of load to be shed for this same case would be 35%. This is because the approximate RoCoF observed in **Figure 3(b)** is about 12 Hz/s. Nonetheless, shedding the entire extra load helped the frequency to get restored in about 1.0 s. From the tests conducted, a maximum of 0.8% overload could only be upheld by the gen-set. The time taken by the frequency to get restored was about 1.5 s. The main parameters of this and the other machines used are presented in the Appendix section.

### 2.2. Wind Generator Load Shed

The wind generator shown in **Figure 5** uses a simple PSS (Power System Stabilizer). The wind turbine model is available in the library of the program used [19]. The main link between the generator and the wind turbine is the mechanical torque ( $T_m$ ) which is set to operate at a constant value. This is because the wind speed and the pitch angle of the wind turbine are also set to be constant at  $W_{SP} = 8$  m/s and  $11.5^\circ$ , respectively.

At  $t = 5.0$  s both loads ( $L_3 = 223.6$  kVA and  $L_{3A} = 300$  kVA) are simultaneously connected (**Figure 6(a)**). At this instant, the generator frequency ( $f_{wnd}$ ) drops to about 58 Hz (**Figure 6(b)**). Notice that the overloading condition (set at  $t = 5.0$  s) and its respective load shedding ( $t = 6.0$  s) result in fast frequency oscillations which are effectively coped by the wind generator speed governor. The rms voltage measured at the busbar where the wind generator is connected to, showed a fair dip during the overload and a slight overvoltage after the disconnection of Load 3A.

Again, if the frequency drop and RoCoF methods were applied, the percentage of load to be shed would be that



**Figure 5. Synchronous wind generator model used.**

exceeding the generator capacity. During this overloading period, the speed regulator damps also these oscillations. Notice that the machine power ( $P_{L3}$ ), and the load current ( $I_{L3}$ ), start dropping steadily (Figure 6(a)). At  $t = 6.0$  s the equivalent extra load (Load 3A) is shed causing the frequency to rise up to about 60.75 Hz, though, becoming damped and stable in approximately 0.5 s. The electric torque ( $T_e$ ) has an opposite behaviour compared to that of the frequency (Figure 6(c)). Due to the conditions specified in the model, the mechanical torque ( $T_m$ ) remains constant at all times.

Wind turbines, especially small ones, are usually prevented from operating under overload conditions. To avoid this condition they are equipped with rigorous protection schemes like the stall and pitch angle control and other protection systems.

### 2.3. Small Hydro-Generator (SHG) Load Shed

The machine dynamics previously described in Section 2.1 (i.e. the diesel generator model) also apply here. The passive load and the unexpected load (equivalent motor), is shown in Figure 7. In this case, two consequences of the load shed procedure were considered.

#### 2.3.1. Successful Disconnection of the Extra Load

It can be observed (Figure 8(a)) that at  $t = 2.5$  s the generator is running at its nominal frequency ( $F_{hydr}$ ) with an

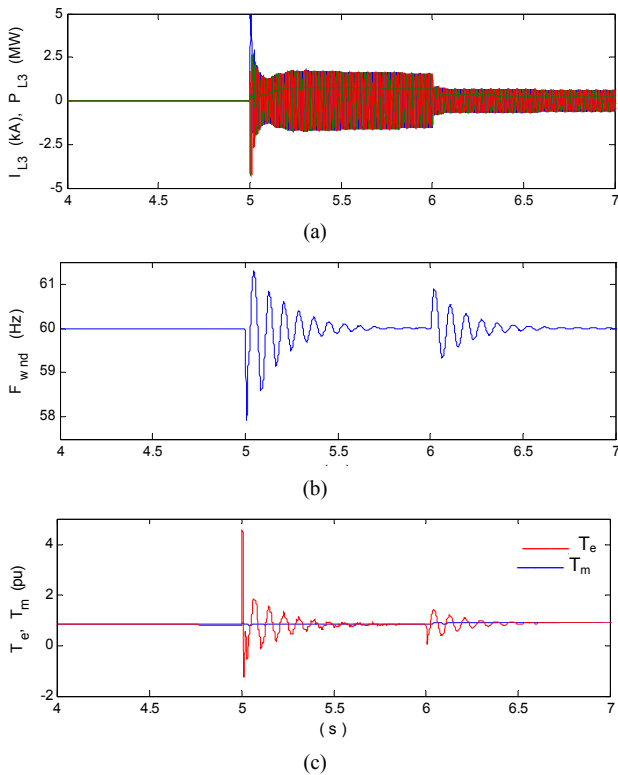


Figure 6. Wind generator: (a) Total load connected; (b) Frequency; (c) Electric and mechanical torques.

initial load ( $L_4 = 0.75 + j0.3$  MVA). Then, at  $t = 3.0$  s, the extra load (i.e.  $L_{4A} = 1.0$  MVA) is connected. The output power in the generator ( $P_{LA}$ ) rises up immediately, though, failing to take up this load until at  $t = 3.5$  s the extra load is shed. The effect of the voltage regulator ( $V_{rms}$ ) in restoring the terminal voltage can be seen in Figure 8(b).

Notice also how after the disconnection of the extra load the machine frequency ( $F_{hydr}$ ) returns to its normal value not before facing some low frequency oscillations

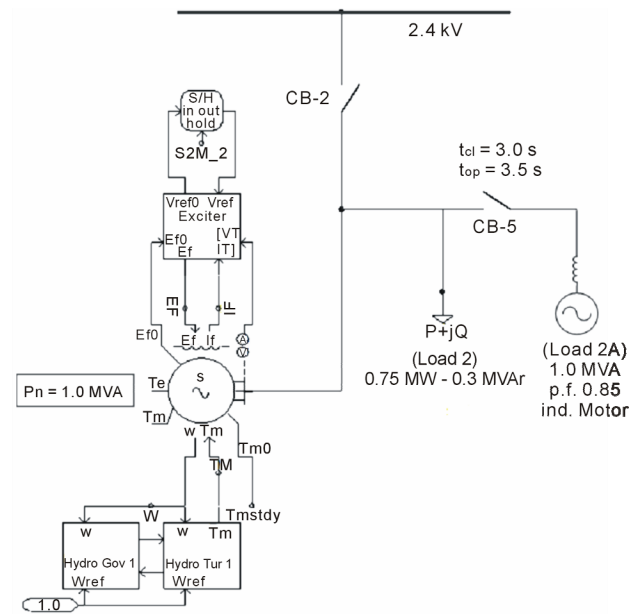


Figure 7. Small hydro-generator model used.

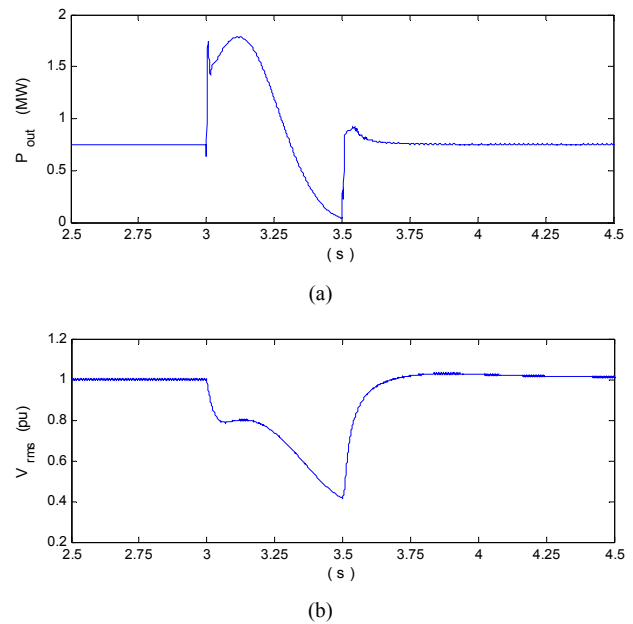


Figure 8. (a) Output power of the SHG; (b) Terminal voltage.

(Figure 9(a)). The electrical and mechanical torque oscillation ( $T_{elt}$  and  $T_{mech}$ ) and their subsequent damping are shown in Figure 9(b).

### 2.3.2. Failure to Disconnect the Excessive (Extra) Load

Failure in disconnecting the extra load will inevitably lead to a steady collapse of the SHG generator. In this case, the switch CB-5 that connects the equivalent extra asynchronous motor is not opened. Similarly to the previous case, the generator initially intends to take up the extra load ( $P_{out}$  in Figure 10(a)); however, due to its limited capacity it quickly drops to zero. Notice that despite the machine has a speed regulator, in situations like this, there cannot be any speed regulator (or power/frequency control) able to cope with such a condition.

A similar falling pattern after the failure to disconnect the extra load can be observed in the case of the SHG terminal voltage ( $V_{rms}$  in Figure 10(b)). Note that nothing was mentioned about the overcurrent protection system which would trip before the current reaches a certain specified threshold.

The steady drop of the SHG frequency (Figure 11(a)) towards the excess load is more evident. Finally, both electrical and mechanical torques ( $T_{elt}$  and  $T_{mech}$  in Figure 11(b)) start up a continuous rise in an effort to fulfill the unexpected load demand.

## 3. Conclusion

The load shedding simulation results of some specific generators within a microgrid are presented in this article. A quick load shed applied to such a microgrid systems, upon which large unforeseen loads are connected, is vital

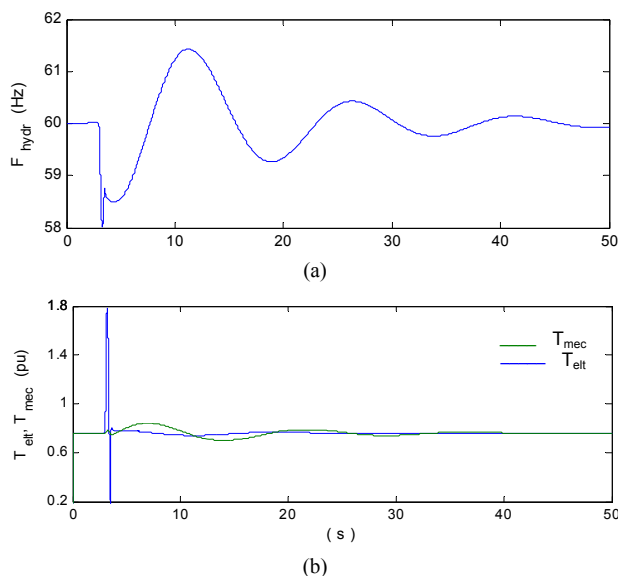


Figure 9. (a) Frequency and (b) electric and mechanical torques of the SHG.

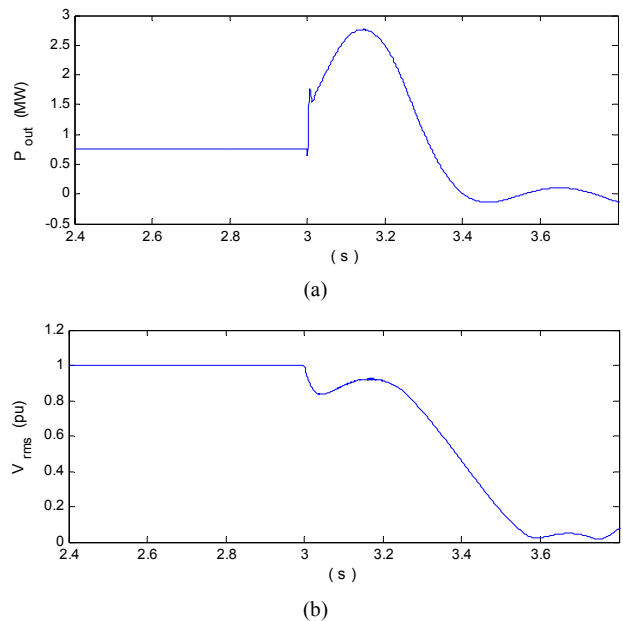


Figure 10. (a) Output power and (b) terminal voltage of the SHG.

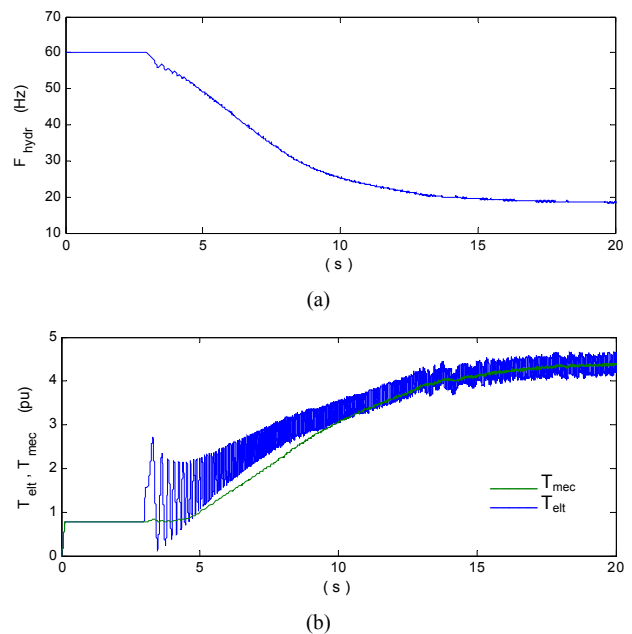


Figure 11. (a) Frequency and (b) electric and mechanical torques of the SHG.

for keeping the generators running normally. Provided their respective voltage and speed regulators all three generators are considered resuming their operation and frequency stabilization after shedding the extra load. On this regard, the article presents the main control components of a gen-set and the various situations which the microgrid generators can face during the transition from the grid connected to the islanded mode of operation. The size and length of time taken to shed the extra load

connected are important factors that can lead to the collapse of the generator and the microgrid itself. Particularly, the size of the extra load accidentally connected will determine the frequency drop and the extent thus the speed regulator will respond.

#### 4. Acknowledgements

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## APPENDIX

The following are the parameters and constants used in the simulations:

$$Z_1 = (0.397 + j0.089) \Omega/\text{km}, L_1 = 1.0 \text{ km}$$

$$Z_2 = Z_3 = (0.460 + j0.104) \Omega/\text{km}, L_2 = L_3 = 0.8 \text{ km}$$

$$Z_4 = Z_5 = (0.55 + j0.130) \Omega/\text{km}, L_4 = L_5 = 2.0 \text{ km}$$

Diesel generator:

- Rotor inertia constant (H) : 0.55 s
- Proportional (P)\* : 5.0
- Integral (I)\* : 40.0 s
- Gain (G) : 1.0
- Time constant (T) : 0.005 s
- Lead time constant (T<sub>1</sub>) : 1.0 s
- Lag time constant (T<sub>2</sub>) : 1.0 s

\*Offer the gen set a stabilizing and damping torque characteristic.

Wind generator:

- Rotor radius : 20 m
- Air density : 1.229 Kg/m<sup>3</sup>
- Gear box efficiency : 0.97
- Angular mech. Speed : 16.667 Hz
- Wind power coefficient (C<sub>p</sub>) : 0.28

Small Hydro Generator:

- Rotor inertia constant : 3.5 s
- Mechanical friction & windage: 0.0 pu