

PROVIDING PREMIUM POWER THROUGH DISTRIBUTED RESOURCES

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Abstract

The modern industrial facility depends on sensitive electronic equipment that can be shut down suddenly by severe power system disturbances. A large number of these disturbances on the power system are a result of line faults which can cause momentary voltage sags. This results in equipment malfunctioning and high restart cost. This paper describes the control of distributed resources as a solution to such problems. In particular the focus is on systems of distributed resources that can switch from grid connection to island operation without causing problems for critical loads.

Introduction

Premium power is a concept, based on use of power electronics equipment (such as custom power devices and active filters), multi utility feeders and uninterruptible power supplies to provide power to users having sensitive loads. This power must have a higher level of reliability and power quality than normally supplied by the utility. With the age of automation, computers, process controls, drives and robotics the quality of electrical power become a major issue. The number of outages, voltage dips and duration is an important issue. In the manufacture of computer chips alone, losses from sags amount to \$1 million to \$4 million per occurrence, according to Central Hudson Gas & Electrical Corp.

Small distributed resources (DR) can increase reliability and power quality by allowing them to be placed near the load. This provides for a stiffer voltage at the load and uninterruptible power supply functions during loss of grid power. The power electronics interfaces found on most small DRs can also control voltage dips and unbalances. Currently, systems for controlling voltage disturbances use a voltage source inverter which injects reactive power into the system to achieve voltage correction. One method is to inject shunt reactive current, the other is to inject series voltage. These systems are effective in protecting against single phase voltage drops (or swells) due to distant faults or unbalanced loads. These systems are costly, complex and are needed only during voltage events. An alternative to these systems are micro-sources with a more robust control system to protection against single phase voltage drops and swells.

Distributed resources (DR) include a variety of energy sources, such as micro-turbines, photovoltaics, fuel cells, and storage devices, with capacities in the 1 kW to 10 MW range. Deployment of DR on distribution networks could potentially increase their reliability and lower the cost of power delivery by placing energy sources nearer to the demand centers. By providing a way to by-pass conventional power delivery systems, DR could also offer additional supply flexibility.

Emerging Technologies

The trends in technology points toward smallness, under the 500kW level. An excellent example are the small gas fired micro-turbines in the 25-100 kW range that can be mass produced at low cost. They are designed to combine the reliability of on board commercial aircraft generators with the low cost of automotive turbochargers. These systems are high speed turbines (50,000-90,000 rpm) with air foil bearings. They are small and use power electronic to interface with the load. Examples include AlliedSignal's 75-kW Turbogenerator, Allison Engine Co's. 50-kW generator and Capstone's 30 kW system.

Fuel cells are also well suited for distributed generation applications. They offer high efficiency and low emissions, but today's costs are high. Phosphoric acid cell are commercially available in the 200-kW range, while solid oxide and molten carbonate cell have been demonstrated.

In October 1997 the U.S. Department of Energy and Arthur D. Little unveiled the "first-ever on-board gasoline powered fuel cell for the automobile". The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. This work is focused towards the polymer electrolyte membrane (PEM) fuel cells.

By 2002, Ballard Power Systems expects to be selling a 250kW PEM fuel-cell based generator at prices competitive with the grid to shopping malls and large commercial buildings. Cinergy Corporation recently placed a commercial order with Ballard for a 250-kW PEM fuel cell for stationary power.

Mixed fuel cell and micro-turbine systems will also be available as distributed generation. In a joint DOE West-

inghouse project a solid oxide fuel cell has been combined with a gas turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 percent with low CO_2 and NO_x and virtually zero SO_x . The expected power levels range from 250-kW to 2.5-MW

Distributed resources include more than small generators and fuel cells. Storage technologies such as batteries, ultracapacitors and flywheel play an important role. Combining storage with micro-sources provide peak power and ride-through capabilities during disturbances. Storage systems are far more efficient than five years ago. Flywheel systems can deliver 700-kW for 5 seconds while 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds.

Areas of Applications

The availability of small, low-cost, power sources provides opportunities for radical change in the structure of power delivery. One of the most basic is to provide firm power. This could be an isolated community, a commercial center or an industrial plant. It is highly probable that gas utilities, and ESCO will be approaching commercial centers and industries to provide firm power using distributed sources. For utility the two prime uses for micro-sources are for peak shaving at the distribution level and to deter or avoid the cost of increasing the distribution infrastructure. Micro-turbines enable distribution to shave peaks through generation rather than demand side management (DSM) techniques. In addition to shaving peaks they also provide capacity for emergencies.

Local generation not only increases overall system efficiency but also reduces investments in traditional generation, bulk transmission and distribution facilities. The utility can also serve incremental load growth in areas where there is a shortage of substation and/or distribution feeder capacity. For this to happen, a method for control and dispatch of 10s-to-100s of units is needed.

Major commercial and industrial users of electrical power pay demand charges to the utility. Micro-turbines could be used to reduce demand charges. In addition to saving in demand charges the turbines could be connected to the more critical loads to provide emergency power. Since all the micro-sources must have a power electronics interface they can all provide the quality of power provided by "Custom Power Devices," such as active filtering, and voltage support during single and three phase disturbances.

Power Electronics & Inertia-less Generation

These technologies require power electronics to interface with the power network and its loads. In all cases there is a D.C. voltage source which must be converted to an ac voltage or current source at the required frequency, magnitude and phase angle. In most cases the conversion will be performed using a voltage source converter with a possibility of phase width modulation to provide fast control of voltage magnitude.

Power electronic interfaces introduces new control issues and new possibilities. A system with clusters of micro-generators and storage could be designed to operate in both an island mode and connected to the power grid. One large class of problems are related the fact that micro-turbines and fuel cell have slow response and are inertia-less. It must be remembered that the current power systems have storage in generators' inertia. When a new load comes on line the initial energy balance is satisfied by the system's inertia. This results in a slight reduction in system frequency. A system with clusters of micro-generators could be designed to operate in an island mode provide some form of storage to provide the initial energy balance.

The control of inverters used to supply power to an AC system in a distributed environment should be based on information available locally at the inverter. In a system with many micro-sources, communication of information between systems is impractical. Communication of information may be used to enhance system performance, but must not be critical for system operation. Essentially this implies that the inverter control should be based on terminal quantities.

It is essential to have good control of the power angle and the voltage level by means of the inverter. Control of the inverter's frequency dynamically controls the power angle, and the flow of the real power. To prevent overloading the inverter and the micro sources, it is important to ensure that load changes are taken up by the inverter in a predetermined manner, without communication.

Basic Component Models

There are two basic classes of micro-source systems; one is a D.C. source, such as fuel cells, photovoltaics, and battery storage, the other is a high frequency ac source such as the micro-turbine which needs to be rectified. In both cases the D.C. voltage needs to be interfaced to the ac network using a voltage source inverter. The time constants for changes in power output for the micro-turbines and fuel cell range from 10 to 200 seconds. This slow

response requires that either the D.C. bus or ac system has storage to insure load tracking. For systems studied in this work, it is assumed that there is battery storage on the D.C. bus to provide fast response to load demands. The general model for a micro-source coupled to the ac system through an inverter is shown in Figure 1.

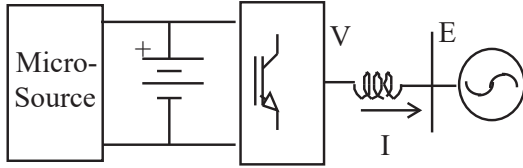


Figure 1. Interface Inverter System

As a minimum the inverter needs to control the flow of real and reactive power (P & Q) between the micro-source and the power system. The P & Q are coupled with P predominantly dependent on the power angle, δ_p , while Q is dependent on the magnitude of the converter's output voltage V . It is also possible to independently control P and voltage E . The equations below indicate that for small values of δ_p and small difference in V & E , the real power P is proportional to δ_p and the reactive power Q depends on voltage difference.

$$P = \frac{3VE}{2\omega L} \sin \delta_p$$

$$Q = \frac{3V}{2\omega L} (V - E \cos \delta_p)$$

The inverter output voltage is not sinusoidal. The inverter output voltage are one of seven vector values, six active and one zero voltages. The inverter output voltage can only switch discretely between these values. These seven vectors transformed to the stationary d-q reference frame are shown in Figure 2.

It is convenient to define a continuous quantity as the time-integral of the inverter output voltage often called the inverter flux vector Ψ_v :

$$\Psi_v(t) = \Psi_v(t_0) + \int_{t_0}^t V d\tau$$

The choice of which vector to apply comes from comparisons of measured Ψ_v and δ_p with the desired values. If the angle δ_p is larger than its reference the zero vector is chosen, since this is the only choice that can reduce the

angle δ_p . If the angle difference is smaller than the specified tolerance, then one of the six states is chosen based on need to increase or decrease its magnitude.

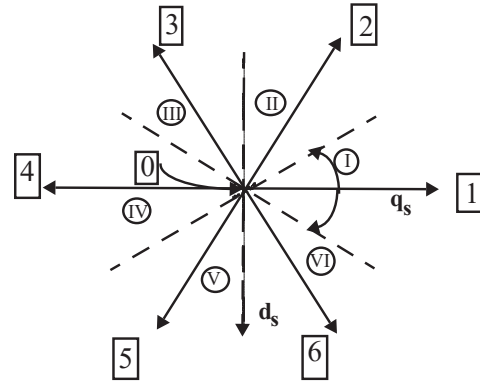


Figure 2. Inverter Output Voltages

A lookup table indexed by sector number and the need to increase/decrease Ψ_v , provides switching logic. Table 1 summarizes the choices for the active vectors. Sectors are also shown in Figure 2. Sector "I" is centered about voltage vector "I". Each time we apply a nonzero voltage vector, we also increasing the value of δ_p .

Table 1: Choice of Switching Vector

	Sector number					
	I	II	III	IV	V	VI
Increase Ψ_v	2	3	4	5	6	1
Decrease Ψ_v	3	4	5	6	1	2

In the most basic application real and reactive powers are assumed to be the controlled quantities as seen in Figure 3. Given set points for real and reactive power, P_0 and Q_0 , the inverter is controlled using the stationary flux vector of the d-q space. The function of the Flux Vector Calculator is to transform phase voltages to the stationary d-q reference frame. The resulting d-q components are time integrated, resulting in the flux vectors, Ψ_v and Ψ_E for the inverter and AC system voltages. This is a concept which is extensively applied to AC motors drives [1]. The two variables that are controlled directly by the inverter are Ψ_v and δ_p , where Ψ_v and Ψ_E are the magnitudes of the inverter and AC system flux vectors respectively, and

δ_p is the spatial angle between the two flux vectors. The vector Ψ_v , is controlled so as to have a specified magnitude and a specified position relative to the AC system flux vector Ψ_E . This control forms the inter-most control loop, and is very fast. The Inverter Flux Vector Control provides the function shown in Table 1. The input set-points, Ψ_{vo} and δ_{po} for the Inverter Flux Vector Control are provided by the P and Q error.

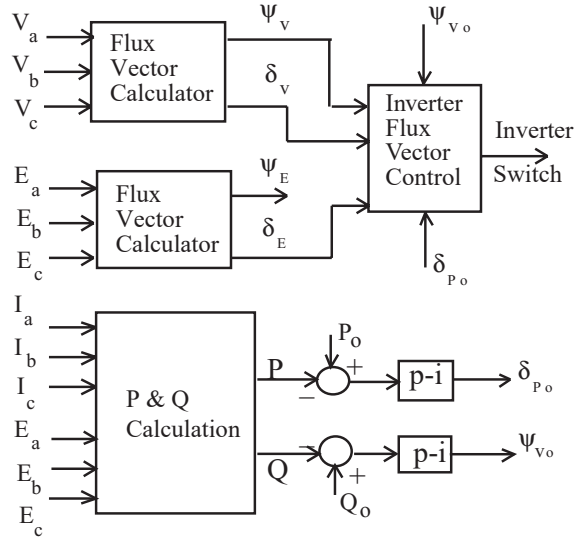


Figure 3. Detailed Inverter Control Scheme

For many dynamic studies where the details of the inverter switching can be neglected the inverter voltage can be represented using a controlled sinusoidal voltage sources. This allows for faster computer simulation, since all the details of the matrix of switches and its firing scheme based on the choice of the switching vector does not need to be implemented. Figure 4 describes the ideal model. Voltage flux magnitude set-point is converted to voltage magnitude with a multiplication by ω_0 , while the angle difference is converted to the inverter phase angle by adding the set-point to the AC side angle, δ_E .

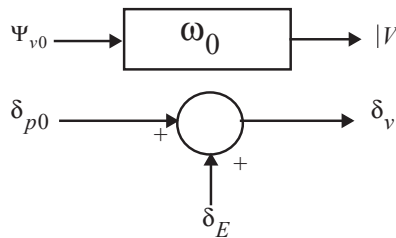


Figure 4. Ideal converter model

For the ideal model the inverter voltages are defined as:

$$V_a = |V| \cos(\omega t + \delta_v)$$

$$V_b = |V| \cos\left(\omega t + \delta_v - \frac{2\pi}{3}\right)$$

$$V_c = |V| \cos\left(\omega t + \delta_v + \frac{2\pi}{3}\right)$$

Figure 5. shows steady state inverter voltage and inductor current traces for both the ideal and full model. The continuous trajectories of current of the ideal model provides an excellent representation of the full model.

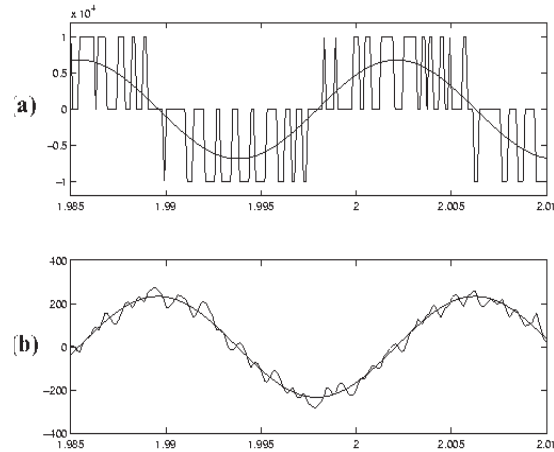


Figure 5. Ideal and detailed models (a) inverter voltage, (b) inductor current.

Figure 6 shows the active and reactive powers response of the controller for the ideal model and the detailed model. The ideal model shows excellent fundamental response, but neglects the harmonics seen in the detailed model. The real power command is increased by 1 pu at $t=1$ seconds. The coupling to reactive power is also apparent. At $t=3$ seconds the reactive power command is increased by 1 pu resulting in a temporary drop in the power level.

The line currents for the increase of the active power (at 3.0 seconds) command is seen in Figure 7. The top trace is for the full model while the lower trace is the ideal model. Again the match is excellent

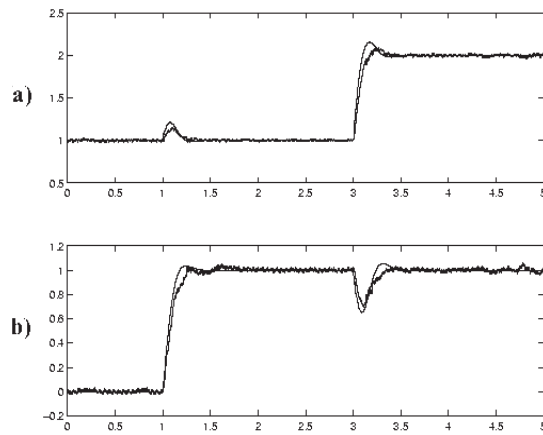


Figure 6. Change in P & Q (a) Active Power pu, (b) Reactive Power pu.

Controls for Grid and Island Operation

Power electronic interfaces introduces new control issues and possibilities. It is necessary to create a power electronic interface, which allows large clusters of micro-generators to operate in both an island mode and as a satellite to the power grid while provide high quality of power at a minimum equipment cost. Basic requirements of the power electronic interface are;

- Provide fixed power and local voltage regulation
- Provide for fast load tracking using storage
- Incorporate "frequency droop" methods to insure load sharing between micro-sources in island operation without communications

An additional possibility, which is not implemented in this paper, is the removal of voltage unbalances by rejecting or canceling the negative sequence components of the supply voltage. For grid connected micro-sources the controls need to provide dispatched power and local voltage regulation. For a system where the distribution feeder and substation are operating near their ratings, micro-sources can be used to defer upgrading the system. The basic operation requires that the feeders are not overloaded. This can be achieved using a control strategy which dispatches to each micro-source the maximum power each load can draw from the grid with the micro sources providing the difference. Another possibility is that each micro-source or cluster of micro-sources are dispatched locally, base on incentives such as cost of grid power, capacity charges or load management agreements

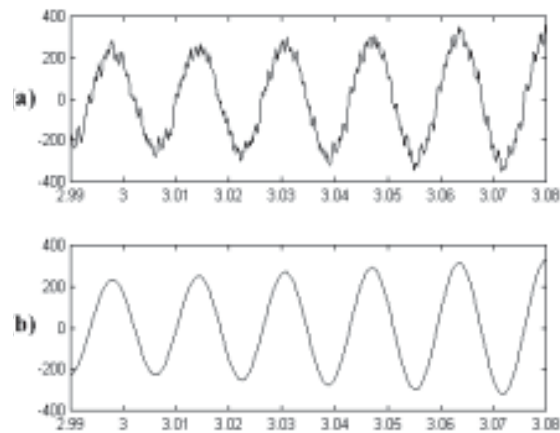
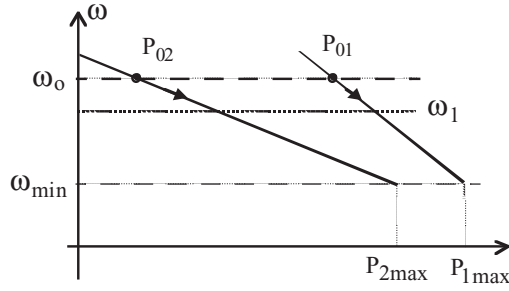


Figure 7. Inductor current during power order change at 3 seconds, (a) detailed model and (b) ideal model.

One large class of problems are related the fact that micro-turbines and fuel cell have slow response and are inertia-less as discussed in the last section. A system with clusters of micro-generators could be designed to operate in both an island mode and as a satellite system connected to the power grid provided storage is present. This could be the kinetic energy of traditional turbines, storage on the ac system or storage on the D.C. bus of each micro-source.

Basic system problems include the control of the power feeder from the grid, speed of response of the micro-source, load sharing and tracking among the distributed resources, reactive power flow and power factor control and steady state and transient stability. The control of inverters used to supply power to an AC system in a distributed environment should be based on information available locally at the inverter. In a system with many micro-sources communication of information between system is impractical. Communication of information may be used to enhance system performance, but must not be critical for system operation. Essentially this implies that the inverter control should be based on terminal quantities.

During islanding operation, the unit has the task of regulating voltage and providing the necessary active power. Such a control must smoothly move from dispatched power while grid connected to power sharing when in the island mode. This can be achieved using local frequency droop as power demand increases. When many machines are located in the same island each machines needs to provide its proportional share of power


 Figure 8. . P - ω droop characteristic

The basic principle that allows the machines to communicate without an explicit network that links them, is to allow the frequency at its terminal to change as a function of power demand. Consider two micro-sources as shown in Figure 8. In this example the sources are assumed to have different ratings, P_{1max} , and P_{2max} . The dispatched power in grid mode is defined at base frequency ω_0 . The droop is defined to insure that both system are at rated power at ω_{min} . The dispatched power can take any level from zero to P_{max} .

During change in power demand these two sources operate at different frequencies causing a change in the relative power angles between them. As this happens, the two frequencies tend to drift towards a lower, single value ω_1 . Note that Unit 2 was operating at a lower power level than Unit 1. At the new power level Unit 2 now provided a larger share of the required power. The basic equation that for droop is:

$$\omega_i(t) = \omega_0 - m_i(P_{c,i} - P_i(t)) \quad \text{Eq.1}$$

Figure 9 shows the details for the droop governor. This governor [2] has two important characteristics: first provides for dispatched value of power when the AC grid is connected; second, when in island mode it provides for power sharing through frequency droop and slowly brings up the frequency back to ω_0 after the droop regulation has reached steady-state

While power adjustment takes place in fractions of seconds, the frequency restoration may take tens of seconds to reach its goal. As the droop regulation may decrease the frequency by one to two Hz, the integrator block will make sure that at steady state the deviation from nominal frequency is very small.

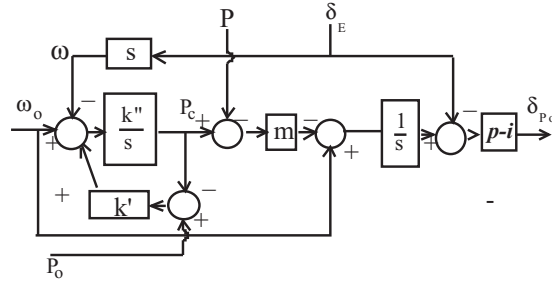


Figure 9. Power Controller with frequency droop

The droop control design comes from the actual consideration that each of the units has a maximum power rating. As a consequence of this, the value of coefficient m_i is dependent on the dispatched power, P_{0i} level while connected to the grid:

$$m_i = \frac{\omega_0 - \omega_{min}}{P_{0i} - P_{max,i}} \quad \text{Eq. 2}$$

The droop power control results in a single new steady state point with a frequency of ω_1 at $t = t_1$ along with a set of different power levels $P_i(t_1)$ for each power source. A control loop is used to uniformly bring the island systems frequency to ω_0 while holding the power levels of each source fixed at $P_i(t_1)$. The rate of changes of frequency for each source must also be held equal to insure fixed power angles between sources. This basic condition implies:

$$\frac{d\omega_i}{dt} = \frac{d\omega_j}{dt} \quad \forall i, j \quad \text{Eq.3}$$

From Eq. 1 the rate of change of ω_i assuming $P_i(t)$ is constant for $t \geq t_1$ is:

$$\frac{d\omega_i}{dt} = -m_i \frac{dP_{c,i}}{dt} \quad \text{Eq.4}$$

Again using the assumption that $P_i(t)$ is constant for $t \geq t_1$ and Eq. 1 it is possible to obtain:

$$\omega_i(t_1) - \omega_i(t) = m_i(P_{c,i}(t_1) - P_{c,i}(t)) \quad \text{Eq.6}$$

Since the frequency restoration loop is much slower than the droop controller it can be assumed that:

$$P_{c,i}(t_1) \approx P_{0,i} \quad \text{Eq. 7}$$

From the integral block of Figure 9 we can write:

$$\frac{dP_{c,i}}{dt} = k''_i[(\omega_0 - \omega_i) + k'_i(P_{0,i} - P_{c,i})] \quad \text{Eq. 8}$$

Substitution of Eq. 4, 6, 7 and 8 yields:

$$\frac{d\omega_i}{dt} = -m_i k_i'' \left[(\omega_0 - \omega_i) + \frac{k'_i}{m_i} (\omega_i - \omega_1) \right] \quad \text{Eq. 8}$$

We want the r.h.s. of Eq. 8 to be equal for all sources or the terms $m_i k_i''$ and k'_i/m_i must be equal for all sources. This implies that gains k'_i and k_i'' are dependent on the set-point $P_{0,i}$ of each system, Eq. 2. If a machine changes its set-point, it doesn't need to communicate to the other machines for this procedure to be successful.

The P, Q controller in Figure 3 needs to be revisited in the light of the new goals of controlling the bus voltage and the P- ω droop. First the Q loop in Figure 3 is replaced with a voltage controller, which includes frequency dependence. The P controller now includes power controller with frequency droop. The details for the full controls are given in Figure 10

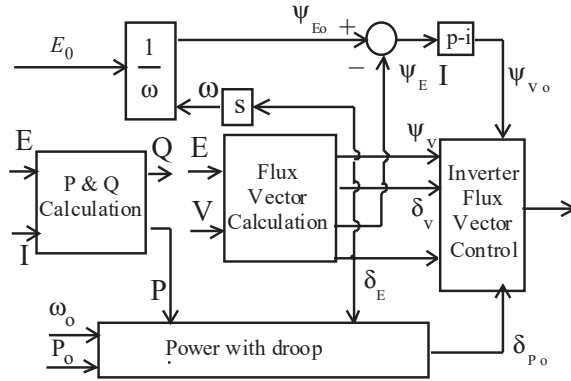


Figure 10. Full controller

Example system

An industrial plant with high motor loads will be used to illustrate the use and control of micro-sources. The industrial site has close to 1 MW of induction motors load, which range from 50 to 150 hp each and two large synchronous machines. Details of the machine loads are summarized in Table 2.

Table 2: Machine Details

	P [MW]	Q [MVAR]
M5 Synchronous	0.24	0.18
M7 Synchronous	0.44	0.0
M8 Induction	0.414	0.28
M9 Induction	0.5	0.34

Electrical power for this load is provide from a 120kV line through a long 13.8kV feeder consisting of both overhead lines and underground cables. The plant has three main feeders; two at 480V and one at 2.4kV. The loads on the 480V feeders are critical and need to survive loss of utility source. Details of the plant are given in Figure 11. and Table 3.

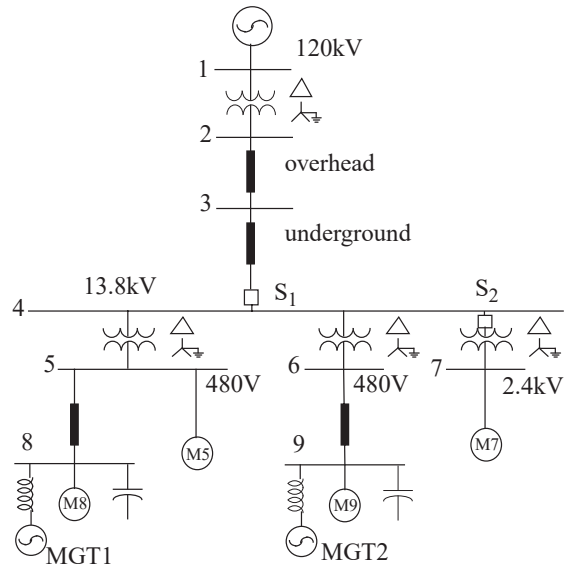


Figure 11. Example system one line

The induction machines clusters M8 and M9 are connected to buses 8 and 9 with capacitive voltage support. Two clusters of micro-sources, MGT1 and MGT2, are also connected Bus 8 and 9 to provide power and voltage support. Without the local generation the voltages of

buses 8 and 9 are respectively 0.933 and 0.941 pu. The total losses are 70 kW.

Table 3: Network Parameters

	$R_{phase}(\Omega)$	$X_{phase}(\Omega)$	$R_{mutual}(\Omega)$	$X_{mutual}(\Omega)$
tmx 1>2	33.55	335.5		
tmx 4>5	1.496	10.47		
tmx 4>6	2.323	13.95		
tmx 4>7	3.48	17.45		
line 2>3	1.5	0.795	2.21	2.67
line 3>4	1.58	0.248	5.15	0.325
line 5>8	0.0127	0.0059	0.0318	0.0148
line 6>9	0.0084	0.0058	0.21	0.0144
cap. 8		-0.921		
cap 9		-0.768		
Ind. 8		0.0069		
Ind. 9		0.0069		

Each cluster of micro-sources are rated at 600 KVA and provide both power injection and local voltage support. The micro-source power injection is approximately one half the total power. With these sources operating the voltages on buses 8 & 9 are regulated at 1 pu and the total losses drop to 6kW.. This is a reduction 64kW.

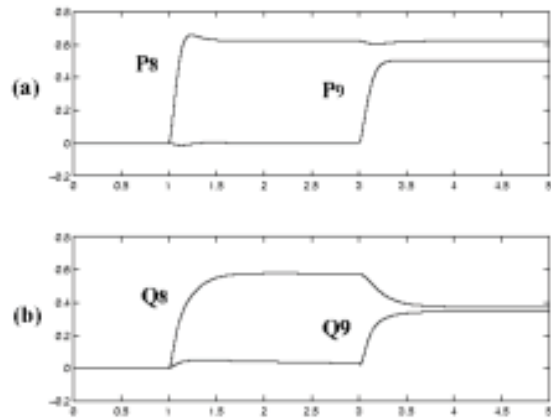


Figure 12. Start-up P & Q of M-T in satellite mode, (a) active power pu, (b) reactive power pu

Simulation of the satellite operation is shown in Figures 12 and 13. The initial state is without the local sources

showing zero real and reactive power injection, and reduced voltages on buses 8 and 9 in Figure 13. At t equals one second the cluster of machines at bus 8 are brought on line with a power setting of 446kW with voltage control. Note the voltage correction in circled area of Figure 13(a)

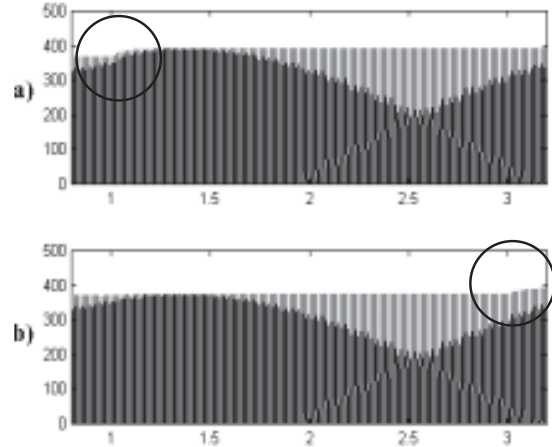


Figure 13. Regulated voltage, (a) buses 8 (b) and 9

At $t=3$ s the units at bus number 9 are brought on line with a power set point of 360kW and local voltage control. Figure 12 shows the active and reactive power injections at the buses where units are located. As the second cluster is brought on line, the Q injection at bus 8 to maintain local voltage magnitude drops. Figure 13 shows half of the voltage envelope at the regulated buses during the start-up sequence. Voltage on bus 9 is controller to 1 pu in fractions of second.

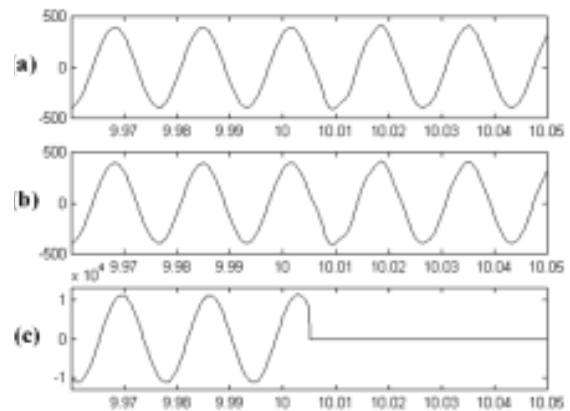


Figure 14. Regulated voltages during transfer to island operation; (a) bus 8 (b) bus 9, and (c) 13.8kv feeder

The second phase of the simulation is focused on island operation. The ratings of the micro-sources are not adequate to supply the total load. It is assumed that the two 480v feeders supply the critical loads and that the M7 load on bus 7 could be dropped using breaker S_2 in Figure 11.

At $t=10$ s the system moves from satellite to island operation by the tripping of switch S_1 due to problems on the supply, Figure 11. At the same time, the non-critical feeder is dropped using S_2 . Waveforms for bus 8 and 9 voltages in correspondence of the switching to island mode are shown in Figure 14. There is only a slight change from the sinusoidal steady state that lasts less than a cycle.

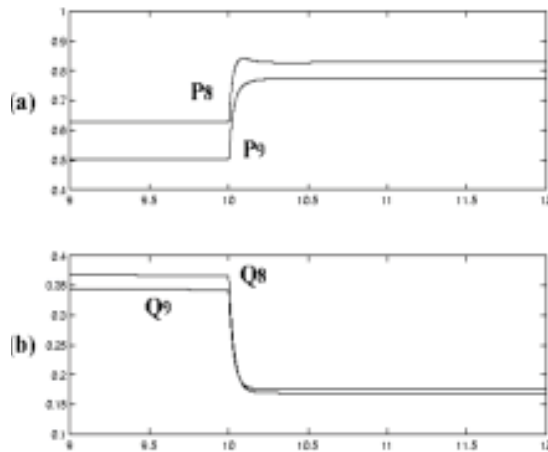


Figure 15. P & Q transient during transition from satellite to island operation.

Figure 15 shows the changes in active and reactive power. Active power has to take up the critical load without grid power. Both machine clusters rise their power injection, and as expected from the design of the droop characteristics. The lighter loaded machine at bus 9 picks up the largest part of the new load demands as seen in Figure 15 (a). Reactive power injection reduces but hold the voltages at 1 pu. The power regulation takes place on a very fast time scale reaching the new steady state power flow in less than a second. The system frequency drooping a little more than 1 Hz. Meanwhile, the frequency restoration loop has started its action and restores the frequency to 60 Hz. Figure 16 shows the frequency restoration of the system. Also note in Figure 15 that the real and reactive power levels stay fixed while the frequency is restored to fundamental

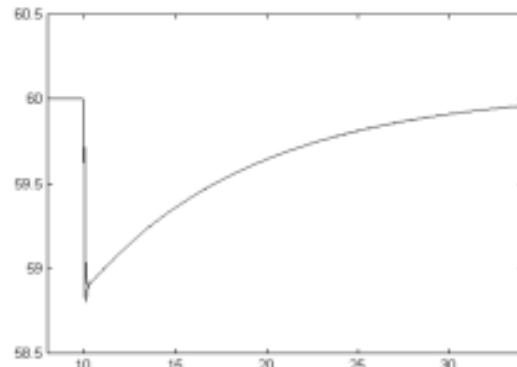


Figure 16. . System frequency in Hz during the transfer from grid connected to island operation.

Conclusion

This work shows how to control micro-sources which can smoothly operate between isolated islands and as a satellite to the power grid. Small power electronics based micro-sources can provide local power, voltage regulation at the load and uninterruptible power supply function using the control concepts presented. Future work will also demonstrate the removal of voltage single phase voltage dips by compensating the negative sequence components of the supply voltage

Acknowledgments

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