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Improvement of Power Control Strategy for Islanded Microgrid Power System

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Abstract

This paper present Improved Active and Reactive Power Sharing Strategies for Electronic Load Controller (ELC) Controlled Synchronous Generator based Islanded Micro Grid (MG) power system. Existing MG at Baglung district was taken as a reference case. For parallel operation each micro hydro plants should shared for active and reactive loads. For this Electronic load controller (frequency controller) and Automatic Voltage Regulator are equipped with droop characteristics. Due to the unequal feeder impedance between sources and loads, reactive power sharing is not in proportion. Sources nearer to the load supplies more power. Sometimes at high reactive load condition one/more generator exceed reactive capability limit and remaining gets free of reactive load. Active power sharing is proportional only if plant active power output is in proportion, but sharing is mismatched if plant active power output is not in proportion with respect to installed capacity/ballast size. Improvements on load sharing has been proposed to minimize the realized limitations and results have been verified using developed MG prototype in MATLAB. Reactive power sharing has been improved by adding reactive droop shifting function within AVR. With this characteristic the generator (whose reactive limit tends to exceed) operates at reduced voltage so that generator operates similar to constant reactive power injection mode, delivering reactive power equals to its limits..Additionally, active power sharing has been improved by designing ELC with dynamic droop regulation. With this approach active droop varies automatically based on actual kW generation so that active power shared by all plant is always proportional to their actual generation. Performance of proposed approach is good for all generating and loading point of MG.

Keywords

Microgrid – micro hydro plant – electronic load controller – dynamic droop – automatic voltage regulator

1. Introduction

Micro Hydro Power plants are very much successful for rural electrification in Nepal as compared to many other countries in the world. Electrification in rural areas by grid extension seems particularly unfeasible in the country because of high transmission/distribution cost, low consumption per household and less number of consumers/sparse load. On the other hand, local resources/streams are abundant. Those are the reasons behind the popularity of MHPs. To increase the utilization factor as well as providing the power sharing and saving opportunity, the concept of Micro Grid (MG) has already been started by interconnecting nearby MHPs. MGs are electricity distribution systems containing loads and distributed energy resources within clearly defined electrical boundaries acting as a single controllable entity with respect to the Utility Grid (UG), that can be operated in a controlled and coordinated way to operate in both grid-connected or island-mode. Electrically, an isolated generator powering a MG is very different from a small generator connected to the UG. The biggest difference lies in who determines the frequency. In the case of an islanded MG the generator controls frequency. In the case of a small plant connected to the UG, the UG controls frequency and the small plants injects electricity in step with the frequency and phase of the UG. Similarly, the role of the generator in voltage control differs for islanded MG and those connected to the UG. On an islanded MG, the generator must control the voltage, while in a UG connected MG, the voltage control at the interconnection point is achieved through coordination of many factors [1]. Thus frequency and voltage control can be considered as the major issues of MG. In MHPs application Electronic Load Controller (ELC) is used to control the frequency. ELC maintains a constant load on the generator by progressively adding/cutting load to the secondary load, until it reaches the exact speed maintaining proper AC frequency. In parallel operation forming a MG, load should be share proportionally by each generators. This can be achieved with the frequency droop characteristics [2]-[3]. Likewise Automatic Voltage Regulator (AVR) is used to control the voltage/reactive power output. In parallel operation small difference in voltage set point causes the significant amount of reactive circulating current. The normal solution is to introduce the voltage droop characteristics within AVR.

2. Baglung Microgrid

The microgrid exhibits 6 Micro Hydro plants i.e. Upper Kalung Khola (12 kW), Kalung Khola (22 kW), Urja Khola I (26 kW), Urja Khola II (9kW), Urjakhola IV (14 kW) & Theulakhola MHP (24 kW), linked in parallel by means of 11 kV transmission line [4]. Turbine, Generator, Transformer, Control and Protection modules are the major equipment of each Micro Hydro Plant. Mostly low head Cross flow and some of multiple nozzle Pelton turbine converts the water energy into mechanical power.

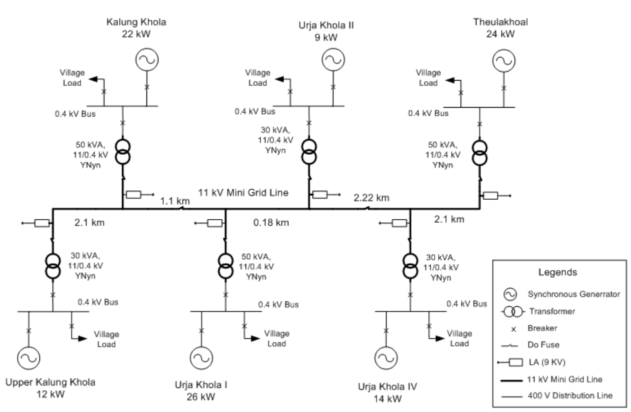


Figure 1: Layout of Baglung Microgrid

Three phase 50 Hz, Star connected Synchronous generators generate electrical power at 400 voltage level. Figure 1 shows the single line diagram of Micro Grid with distributed MHPs. One feeder distributes electricity to nearby consumer and next feeder connect with MG. Approximate 8 km long, 11 kV transmission line acts as a power pool for MHPs. Independent Power Producer (IPP) modality was adopted for its management. Each of MHPs sells electricity to Micro Grid Operator (MGO) and MG is responsible for the distribution of electricity. Only hand hoist mobiles phones are use as communication medium among MHPs and between MHPs and MGO.

2.1 Operation of ELC

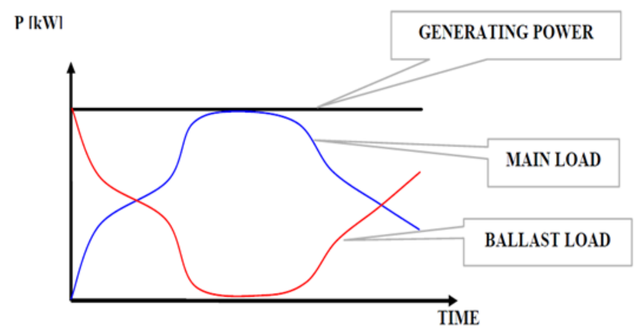


Figure 2: Power Balance Principle of ELC

An ELC is an electronic governor that functions as a frequency regulator on a generator by diverting surplus electrical power to a resistive dump load. Dump load (Also known as secondary/ballast load.) are activated by an ELC to dissipate power that is not required by the user load, making

Generating Power = Ballast Load + Main Load (Fig. 2) [5].

Frequency is the variable that needs to be controlled. The difference between measured value of frequency (F) and desired reference frequency (Fref) gives error signal i.e.,

$$\Delta F = F_{ref} \times F$$

Power is to be dissipated by the secondary load is determined by the error signal. This error signal is passed through the PI Controller to get the firing angle i.e.,

$$\alpha = K_P \times \Delta F + k_i \int \Delta F \times dt$$

Kp and Ki are proportional and Integral gain of PI Controller. Usually Thyristors are fired at such firing angle to dissipated desired secondary power.

$$P_o = \frac{V_s^2}{R}\left[\frac{1}{\pi}(\pi - \propto) + \frac{Sin(2\alpha)}{2}\right]$$

P0 is the power consumed by the secondary load of resistance (R) at firing angle of an AC signal with per phase RMS Value Vs.

$$R_{\text{Per Phase}(\Omega)} = \frac{3 \times V_s^2}{K \times MHP_{kW}}(\alpha = 0)$$

Dump loads are electrical resistive loads sized equal to or be slightly greater than rated capacity of plant. Usually ambient air or water heaters are used as dump load in general application. K is the secondary load multiplication factor and normally considered around 1.2.

2.2 Frequency Droop Characteristics

Isochronous frequency control cannot be used when two or more generators are operating in parallel. For parallel operation each generator would have precisely same frequency/speed setting. Otherwise, they will fight each other, each trying to control the system frequency to their own setting. For stable load division, the frequency controller/governors are provided with a characteristic so that the speed drops as the load is increased [6]. The droop characteristic is designed based on the secondary load size. As the secondary load increases frequency increases or conversely as the main load increases frequency droops. The droop characteristic can be obtained by operating the generator at no and full secondary load (Fig. 3).

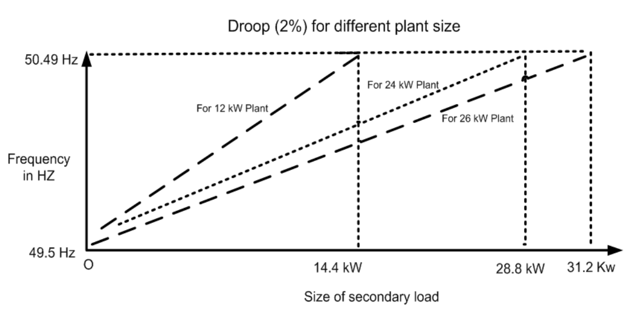


Figure 3: Frequency droop characteristics of ELC

Frequency stabilizes to its upper set point at full secondary load and stabilizes to its lower set point at no secondary load. The regulation can be evaluated from frequency droop characteristics as:

$$\text{Droop} = \frac{\text{Percentage Speed/frequency Change}}{\text{Percentage Chagne in Ballast Power}} \times 100$$

$$R = \frac{\Delta F}{\Delta P_b}$$

$$F = F_0 + R \times \Delta P_b$$

So, for any change in secondary load, corresponding steady state frequency can be estimated. The droop is obtained taking steady state positive feedback across the PI controller (fig 4).

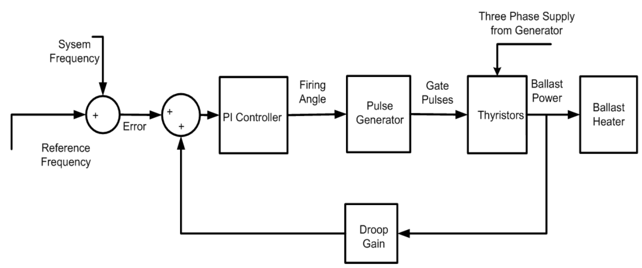


Figure 4: Block diagram of droop control strategy

The controllers are tuned manually. Power is taken as feedback signal. The advantage of secondary load power feedback is that it will make the linear relationship between frequency and secondary load.

2.3 Voltage Droop Characteristics

AVR is used to control the excitation of synchronous generator which is then controls the terminal voltage as well as reactive power injection to the microgrid. AVR builds up the terminal voltage to a desired level and maintains the air gap flux to maintain desired terminal voltage of generator. The simplified block diagram of AVR designed as synchronous generator voltage/reactive power controller is shown (fig. 5).

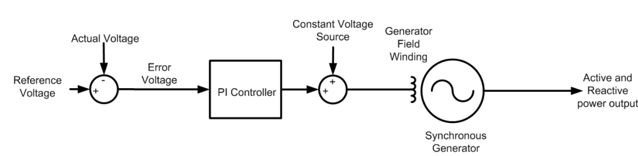


Figure 5: Generalized block diagram of AVR (Isochronous Mode)

AVR constantly monitors the terminal voltage of generator. Any deviation on terminal voltage than desired reference value causes an error signal. The error signal is passed through PI controller to generate a voltage signal which is added to a constant voltage source to obtain excitation field voltage, which is then applied to the field winding of the generator to maintain desired terminal voltage equal to the reference value. For the parallel operation, AVR should be incorporated with voltage/reactive droop characteristics. The voltage/reactive droop can be obtained by adding a steady state feedback loop across the PI controller. The block diagram of AVR with voltage droop characteristics is shown in (fig. 6).

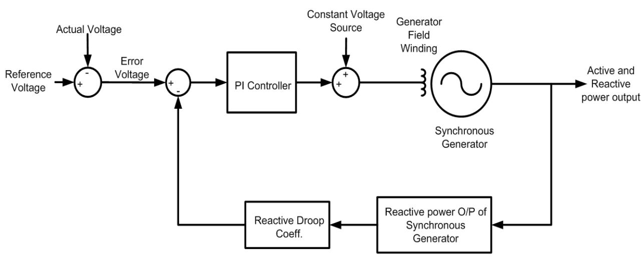


Figure 6: Generalized block diagram of AVR (Droop Mode)

The feedback loop calculated the voltage deviation corresponding to the reactive power supplied by the generator. The deviation of voltage depends upon the droop coefficient. 5

2.4 Computational Model

For simulation purpose MG with three MHPs i.e. 12 kW, 26 kW and 24 kW was considered, due to simulation limitation in the computational tools. However, the model will capture all the information of the complete model. Local load (three phase resistive as well as inductive loads) is connected at low voltage side of each MHP. ELC and AVR are used for frequency and voltage control of each MHP (fig. 7)

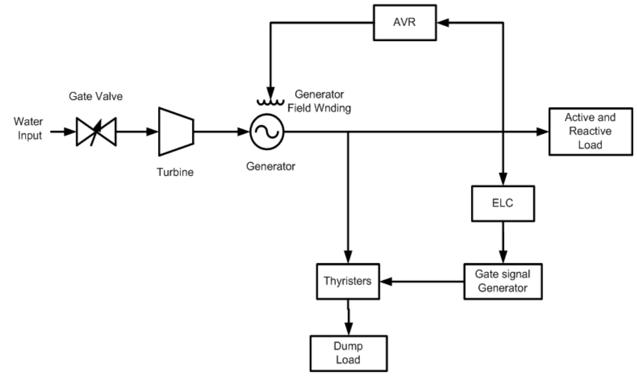


Figure 7: Micro Hydro Model

Weasel conductor with resistance of 0.9116 Ω/phase/km & inductance of 1.147×10^{-3} H/ph/km is taken at high voltage transmission line.

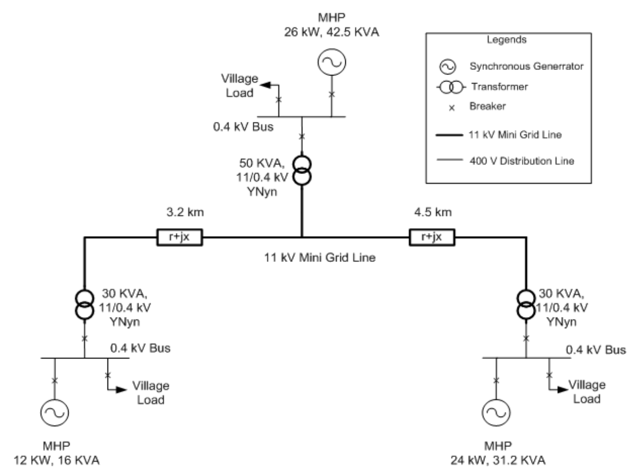


Figure 8: Computational Model

General layout consider for case study is shown. (fig. 8). The system is then translated in the MATLAB/Simulink© environment. The specification and parameters considered for simulation purpose are summarized (table 1).

Table 1: MHP Parameters

S. N.	MHP (kW)	Generator (kVA)	Sec. Load (kW, Line V)	Ballast Resistance Per Phase (Ohm)	Ttransformer (kVA/kV/Group)
1.	12	16	14.4, 400	11.020	30,11/0.4, Ynyn
2.	26	42.5	31.2, 400	5.086	50,11/0.4, Ynyn
3.	24	31.3	28.8, 400	5.510	50,11/0.4, Ynyn

2.5 Estimation of Reactive Power Capability limit

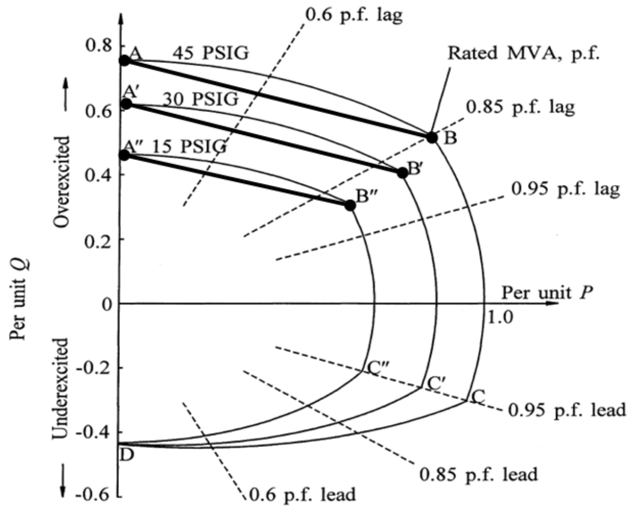


Figure 9: Generator Cability Curve

Synchronous generators are rated in terms of maximum MVA output at a specified voltage and reactive power factor which they can carry continuously without overheating. The active power output is limited by the prime mover capability to a value within MVA rating. The continuous reactive power output capacity is limited by three considerations: a) armature current limit, b) field current limit and c) end region heating limit.

Figure 9 shows the reactive capability curve of a 400 MVA hydrogen-cooled generator at rated armature voltage. The base MVA in this case is the rated MVA at 4 PSGI (pounds/square inch gauge) hydrogen pressure. For each pressure, segment AB re presents the field heating limit, segment BC the armature heating limit, and segment CD the end region heating limit.

In figure the loci of constant power factor is also shown. Since the point of intersection of armature current limit and field current limit gives the rated MVA and rated p.f. of generator, above the rated p.f. armature current limit is critical and below the rated p.f. the field current limit is critical. Moreover it is difficult to calculate the field current limit since its calculation requires generator parameters which are not easily available. So the field current limit can be simplified by a straight line segment passing through intersection point of both limit and that of field current limit and Q axis on P-Q plane. Hence the equation of field current limit as represented by the straight line segment AB can be simplified to:

$$Q_{\text{field Limit}} = (0.75 - 0.27 \times P) \times S$$

Where S is the MVA rating and P is the per unit active power supplied by generator. Likewise armature current limit of generator can be estimated by:

$$Q_{\text{armature lim}} = \sqrt{1 - P^2} \times S$$

So, reactive power limit of MHPs generator be estimated as: Minimum of armature and field current limit i.e. Reactive power limit = Smaller of field limit and armature limits.Using the above equation, at any kW loading corresponding reactive power limit can be estimated.

3. Simulation Results

Simulation is performed by considering several cases. The current load sharing strategy is analyzed and problem in existing system is realized. Load is changed at suitable interval. The accuracy of active power sharing is expressed in terms of percentage error. Separate active and reactive power balance tables are then presented for various cases. Two percentage active droop and upper and lower voltage limit of reactive droop are 230 V and 220 V are considered. All the powers are measured and results are presented in power balance table.

Case-I (Active Power Sharing Realization)

Table 2: Active Power Balance Table (a)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	11.53	3.74	-0.06	7.8	3.71	3.68	-0.83
26	25.16	7.64	0.61	16.9	8.10	8.25	1.88
24	22.81	7.58	-0.36	15.59	7.34	7.22	-1.65
Total	**59.5**	**18.96**		**40.29**	**19.15**	**19.15**	

Table 3: Active Power Balance Table (b)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	5.63	3.82	-2.33	4.14	2.68	1.49	**-44.31**
26	19.59	7.73	2.83	9.02	9.31	10.56	**13.42**
24	15.81	7.69	-0.24	8.36	7.51	7.45	**-0.85**
Total	**41.03**	**19.24**		**21.52**	**19.50**	**19.50**	

Table 4: Active Power Balance Table (c)

Plant (kW)	Generation (kW)	Local Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	4.14	3.82	-5.67	5.98	1.59	-1.85	-216.20
26	24.27	7.66	3.51	13.09	9.33	11.17	19.68
24	22.22	7.71	2.44	12	8.54	10.15	18.79
Total	50.63	19.19		31.07	19.47	19.47	

Active power sharing is proportional only if plant active power output is in proportion, but sharing is mismatched if plant active power output is not in proportion with respect to installed capacity/ballast size. Due to this, at some loading/generation condition ballast of one plant acts as load of other plants i.e. MG feeds to the ballast load. This causes financial implications to MHPs.

Case-II (Reactive Power Sharing Realization)

Table 5: Reactive Power balance Table (a)

Plant (kW)	Generation (kVAR)	Gen. Limit (kVAR)	Load (kVAR)	Grid Power (kVAR)	Ballast load (kVAR)	Load Shared (kVAR)	Bus Voltage (Volts)
12	7.3	7.99	3.3	-0.42	4.42	2.88	220.70
26	14.52	22.56	2.53	1.99	9.99	4.52	223.43
24	12.38	15.57	3.28	-1.34	10.43	1.94	221.84
Total	34.2	46.12	9.11		24.84	9.34	

Table 6: Reactive Power Balance Table(b)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	5.63	3.82	-2.33	4.14	2.68	1.49	-44.31
26	19.59	7.73	2.83	9.02	9.31	10.56	13.42
24	15.81	7.69	-0.24	8.36	7.51	7.45	-0.85
Total	41.03	19.24		21.52	19.50	19.50	

Table 7: Reactive Power Balance Table (c)

Plant (kW)	Generation (kVAR)	Gen. Limit (kVAR)	Load (kVAR)	Grid Power (kVAR)	Ballast load (kVAR)	Load Shared (kVAR)	Bus Voltage (Volts)
12	11.73	8.09	9.6	-1.75	3.88	7.85	215.42
26	15.91	22.56	4.23	2.56	9.12	6.79	222.88
24	18.25	15.64	11.35	-1.64	8.54	9.71	218.26
Total	45.89	46.29	25.18		21.54	24.35	

Due to the unequal feeder impedance between sources and loads, reactive power sharing is not in proportion. Sources nearer to the load supplies more power which is beneficial. Sometimes at high reactive load condition one/more generator exceed reactive capability limit and remaining gets free of reactive load. This may damage the voltage regulating device as well as generator field/stator windings by exceeding the limits.

3.1 Improvement on Active power Control

The output of MHPs is flow dependent and is highly variable so operation of MHP at rated capacity through the year is impossible. In order to solve the imbalance in power sharing droop regulation with dynamic characteristics is proposed. The basic concept is that, the droop is regulated dynamically such that secondary load behaves as reduced size within the standard frequency range. The result of this is that, the secondary load consumes only generated power (at max) within standard frequency dropping range. This makes secondary load size in proportion to the actual generation compensating the reduced generation capacity of MHP. Figure 10 shows the unity dynamic droop characteristics of MHPs.

From dynamic droop characteristics (Fig. 10) it can be showed that when MHP operates at half of rated capacity the regulated droop is 4% and so on. This means that 2% change in frequency causes 50% change in ballast power. Such regulation restricted the operation of MG outside standard frequency range as long as cumulative generation is greater than or equal to cumulative load plus active power losses of MG.

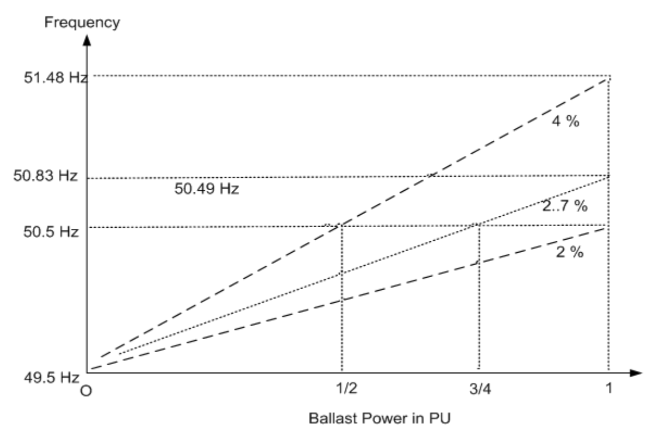


Figure 10: Dynamic Droop Characteristics

3.2 Improvement on Reactive power Control

In order to minimize the imbalance in reactive power sharing addition of dynamic droop shifting function within automatic voltage regulator is proposed. With droop shifting characteristic the generator operates at reduced voltage so that the reactive power supplied by generator is always within its limit. The droop shifting function is effective only after the reactive power supplied by generator reaches its limit.

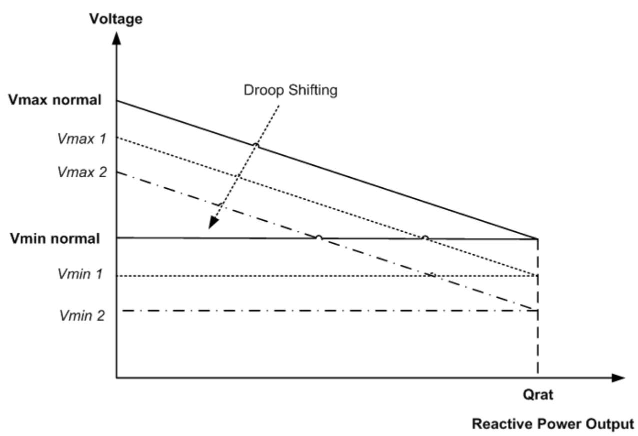


Figure 11: Droop Shifting Characteristics

With this characteristic the generator whose limit is reached operates at reduced voltage so that reactive power will flows from other generator busbar. The process is continues until total reactive demand of microgrid is less than total reactive power capability of microgrid.

The reactive droop characteristic of a generator with droop shifting function is shown in figure 11. As shown (fig. 11), when generator operates at normal droop range, voltage varies from Vmax normal to Vmin normal.When reactive power tends to increase beyond limit the droop shifts downward with voltage range Vmax1 to Vmin1 so that reactive power supplied remains equal to Qrated.

3.3 Simulation Results of of Proposed Scheme

Likewise, as in the modeling of existing system various cases are taken for simulation and results are presented in the form of power balance table. The mismatch in power sharing is calculated in terms of percentage error.

Table 8: Active Power balance Table (a)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	11.47	9.78	-2.4	4.1	7.36	7.38	0.21
26	25.15	15.09	1.06	8.99	16.15	16.15	0.01
24	22.81	13.05	1.58	8.17	14.65	14.63	-0.11
Total	59.43	37.92		21.26	38.16	38.16	

Table 9: Active Power balance Table (b)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	5.7	3.79	-1.11	3.02	2.69	2.68	-0.28
26	19.56	7.68	1.55	10.32	9.22	9.23	0.08
24	15.8	7.63	-0.18	8.34	7.45	7.45	0.00
Total	41.06	19.1		21.68	19.36	19.36	

Table 10: Active Power balance Table (c)

Plant (kW)	Generation (kW)	Load (kW)	Grid Power (kW)	Ballast load (kW)	Load to be Shared (kW)	Load Shared (kW)	Error %
12	4.21	3.83	-2.22	2.6	1.61	1.61	-0.14
26	24.31	7.64	1.66	14.99	9.31	9.3	-0.10
24	22.29	7.7	0.848	13.74	8.54	8.548	0.14
Total	50.81	19.17		31.33	19.46	19.46	

In all cases the errors in active power sharing are negligible. Unlike that of existing droop strategy the 12 kW MHP does not violets its reactive capability limits. With proposed approach the error in active power sharing is negligible at all generating points.

Table 11: Reactive Power balance Table (a)

Plant (kW)	Generation (kVAR)	Gen. Limit (kVAR)	Load (kVAR)	Grid Power (kVAR)	Ballast load (kVAR)	Load Shared (kVAR)	Bus Voltage (Volts)
12	7.28	7.99	3.3	-0.43	4.41	2.87	220.70
26	14.53	22.57	2.53	2.07	9.92	4.6	223.40
24	12.35	15.58	3.28	-1.4	10.47	1.88	221.78
Total	34.16	46.14	9.11		24.80	9.35	

Table 12: Reactive Power balance Table (a)

Plant (kW)	Generation (kVAR)	Gen. Limit (kVAR)	Load (kVAR)	Grid Power (kVAR)	Ballast load (kVAR)	Load Shared (kVAR)	Bus Voltage (Volts)
12	8.01	8.01	6.4	-2.36	3.97	4.04	216.30
26	16.31	22.57	4.22	3.93	9.15	8.15	222.72
24	13.67	15.57	4.95	-0.24	8.96	4.71	221.17
Total	37.99	46.15	15.57		22.08	16.90	

Table 13: Reactive Power balance Table (a)

Plant (kW)	Generation (kVAR)	Gen. Limit (kVAR)	Load (kVAR)	Grid Power (kVAR)	Ballast load (kVAR)	Load Shared (kVAR)	Bus Voltage (Volts)
12	8.02	8.02	10.75	-3.23	3.76	7.52	208.42
26	20.63	22.62	14.81	7.34	9.12	22.15	220.83
24	15.62	15.62	12.05	-3.47	8.39	8.58	211.76
Total	44.27	46.26	37.61		21.27	38.25	

When the reactive power supplied by 12 kW MHP tends to violet its limits, the reactive power output is increases only upto its reactive power capability limit and so on for 24 kW MHP. Further increase in reactive power demand will be supplied by 26 kW MHP.

4. Outputs Graphs

The output curves show the limitations of reactive power sharing (Fig.12-14) and improvement with proosed strategy (Fig15-17). Due to the droop, frequency is stabilized at slightly lower value after change of load (Fig. 18). Likewise the voltage response is also regulated at its rated value (Fig. 19).

Figure 12: Reactive Power Limit & Gen. of 12 kW MHP

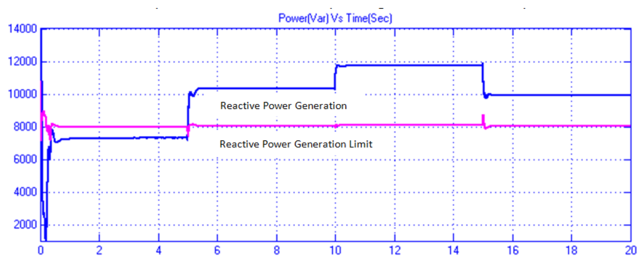


Figure 13: Reactive Power Limit & Gen. of 26 kW MHP

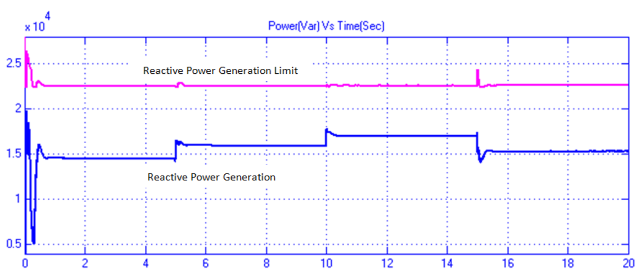


Figure 14: Reactive Power Limit & Gen. of 24 kW MHP

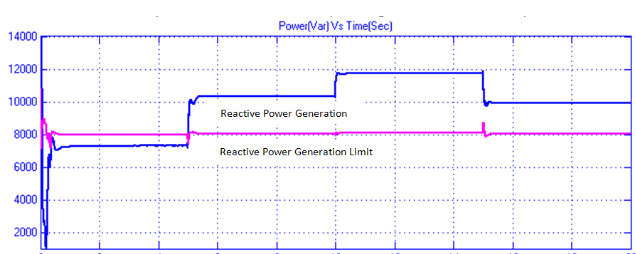


Figure 15: Reactive Power Limit & Gen. of 12 kW MHP

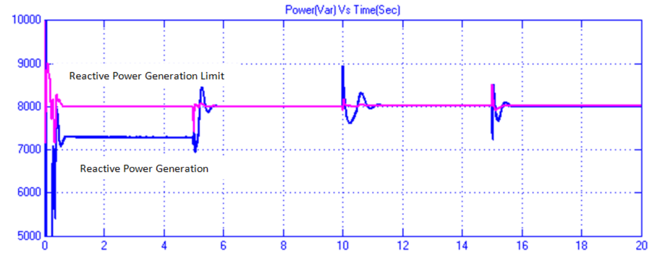


Figure 16: Reactive Power Limit & Gen. of 26 kW MHP

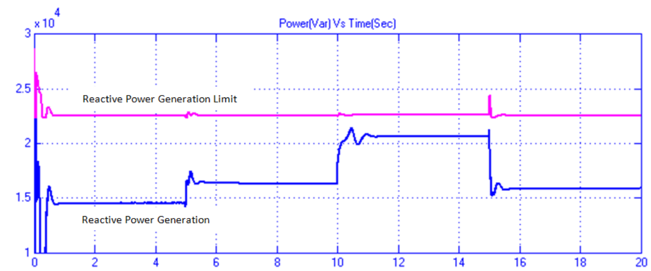


Figure 17: Reactive Power Limit & Gen. of 24 kW MHP

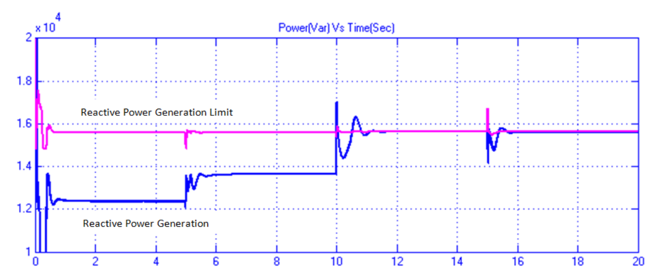


Figure 18: Output Graph of Frequency

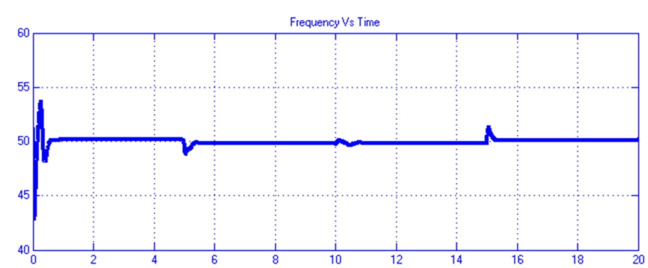
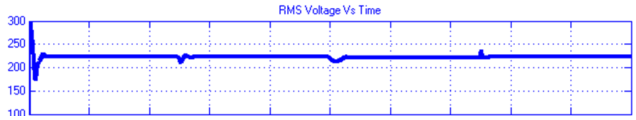


Figure 19: Output Graph of Voltage



5. Conclusion

With droop characteristics active power sharing is proportional but reactive power sharing is not in proportional due to mismatch in line impedance between sources and load. The unequal reactive power sharing sometimes results that some generators will violets their reactive power limit and other are under loaded. Moreover, active power sharing error is increased if all plants are not generating proportional Outputs.

Such limitations of reactive power sharing can be minimized by adding the reactive droop shifting function within AVR. With droop shifting characteristic the generator operates at reduced voltage so that the reactive power supplied by generator is always within its limit. Likewise the, limitation of active power sharing can be minimized by designing ELC with dynamic droop regulation. With this approach active droop coefficient varies automatically based on actual generation so error in active power sharing is minimized.

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