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Voltage and Frequency Regulation of Islanded Microgrid with Multiple Conventional Generators

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Abstract*—This paper investigates the problem of voltage and frequency instability at islanded mode of microgrid. Load variations in the microgrid, can lead to imbalance between the power supply and demand, thereby resulting in the instability of voltage and frequency. In the proposed approach, an islanded microgrid has been modelled with the conventional distributed generation units and loads. Voltage and frequency regulation approach has been proposed. The power dispatching strategy of the conventional generators is based on the combination of the voltage and frequency droop control and PI control. In the studied 2MW microgrid system, all power is provided by the local distributed generations. Frequency and voltage droop controllers have been developed for the regulation of voltage and frequency. Balanced active and reactive power sharing of parallel operating generators has also been achieved. The proposed methodology has been implemented in MATLAB/Simulink environment and results have proved the strength of the suggested methodology.

***Keywords*— Islanded microgrid, voltage and frequency stability, droop control, conventional generation**

I. INTRODUCTION

Currently, the integration of distributed energy resources has been rapidly increased into the distribution networks. Microgrid can operate in grid-connected mode or autonomous mode (islanded mode) of operation. In case of grid-connected operation, main utility is responsible for all power generation. In islanded mode of operation, these distributed generation units provide power to meet the load demands without taking the power from the utility. Extra amount of generated power in islanded microgrids can be stored in batteries or can be exported to the utility. Regulation of voltage and frequency at islanded mode is very crucial, as at the same time, balanced load sharing, reliable and secure power supply must be provided to the consumers. Generally, a droop control based approach is adopted for islanded mode. The main feature of droop control is wireless control [1, 2]. There are some restrictions in implementation of this approach. For example, change in the impedance of power lines. The impedance variation can lead to unproportioned power sharing by distributed generators. [3, 4] and decreased values of V-f droop coefficients [5].

Lots of contributions have been made by the researchers to provide the solution of microgrid regulation and power sharing problems. A virtual-impedance based approach has been proposed in [2, 6] to balance the impedance variations. But, this approach is not accurate in terms of real and reactive power sharing at islanded mode [7]. In [8] a control method has been implemented for a gas-engine generator with battery energy storage system. A combination of the control of synchronous generator and improved droop control method has been proposed by [9]. It can be utilized to enhance the frequency and voltage regulation of the microgrid. Virtual synchronous generator based controllers have been developed by [10] for the transient analysis of microgrids [10]. This approach has resulted in minimization of the transient power oscillation. The active power-frequency based droop control loop has been developed by [11] to satisfy the load changes as per the output of the generating capacity of DGs.

The V-Q (Voltage-reactive power) based droop control method has been developed [12] for the regulation of voltage in power system. Droop control methods are simple and are independent of communication network, which makes it cheap and reliable control method [13]. There are some challenges associated with the conventional droop control based approaches as listed below.

- Droop controllers output is dependent on power network impedance [14].
- Cross-coupling of V-Q and f-P droop loops [15].
- Unreliable output of the droop coefficients in the presence of complex loads, renewable DGs and electric vehicles.
- Poor transient performance in large distribution networks.
- Inconsideration of load dynamics.
- Performance dependency of droop control on values of droop coefficients.

To overcome these challenges, lots of contributions have been added by the potential researchers. Communication based distributed control methods have been developed by [16]. Adaptive and arctan droop control has been proposed in [17] and [18] respectively to improve the dynamic stability. A master-slave, a communication free approach has been suggested by [19] for accurate power distribution in microgrid. De-loading technique has been applied by [20] for power sharing and frequency regulation of microgrid. But at the islanded mode of operation still efforts are being made. Islanded microgrid face issues of stability and harmonic sharing;

with the incorporation of non-linear, complex pulsed loads, distributed generation and electric vehicles [21].

In the proposed approach an improved droop control mechanism for operation of islanded microgrid has been developed. It consists of two droop controllers for frequency and voltage regulation. To provide balanced active and reactive power to the loads, in addition to the droop controllers, a PI controller has also incorporated. Different load change cases have been simulated to validate the proposed controller performance.

The paper is organised as follows. In section 2 the studied system description has been presented. In section 3 the control methodology has been described. In section 4 case studies have been presented. Conclusion and references has been provided in sections 4 and 5 respectively.

II. SYSTEM DESCRIPTION

The studied microgrid system has been developed with the parallel operating conventional generators and loads.

A. Conventional Generators

In conventional power systems, major electricity demand is provided by the synchronous generators. Conventional synchronous generators produce electricity by converting the mechanical energy into electrical energy. Basic model of conventional generator has been presented in Fig. 1. It consists of excitation system, governor control, power system stabilizer and automatic voltage regulators [22].

In studied power system two three-phase synchronous generators rated at 1 MW, 400 V, 60 Hz has been installed in the microgrid. Synchronous generators have been modelled in the d-q rotor reference frame .An islanded mode of microgrid has been considered for the experimentation and case studies.

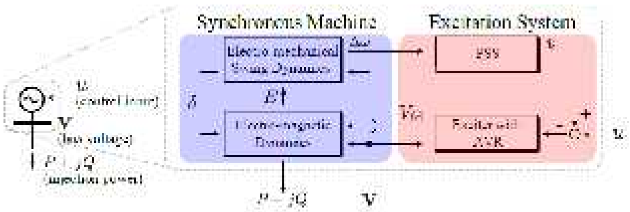

Fig. 1. Synchronous generator model

B. Excitation System

There are different types of excitation systems of synchronous generators. IEEE has also developed some standard excitation system models for stability analysis [23]. The studied excitation system consists of voltage regulator, compensator, filters, exciter and stabilizer. This kind of system ensures voltage stability and handles the damping effect. The excitation system can be represented by the following equation.

$$V_f = \frac{1}{\tau_e}\left(-V_f + V_f^{*} + V_e\right) \quad (1)$$

$$V_e = K_e(|V| - |V|^{*} - v + u) \quad (2)$$

The transfer function of exciter is given below.

$$\frac{V_f}{V_e} = \frac{1}{K_e + s\tau_e} \quad (3)$$

Where

τ_e	Time constant of exciter
K_e	Voltage regulator gain
V_f	Field voltage step point
V_e	Exciter field voltage
$\lvert V\rvert^{*}$	set point of Voltage
v	Stabilizer output
u	Additional voltage to AVR

Parameters of developed excitation system have been listed in Table 1.

TABLE 1: PARAMETERS OF EXCITATION SYSTEM

Parameters	Value
AVR gain	350
AVR time constant	0.001
Excitation system gain	1 (1 to 2)
Excitation system time constant	0.2 (0 to 0.7)
LP filter time constant	0.002
Damping filter gain	0.001
Damping filter time constant	0.1
AVR output limits	-10.5-10.5

C. Power System Stabilizer

Power system stabilizer provides aid in damping effect of rotor and contributes in frequency stability [24]. Power system stabilizer can be represented by following transfer function. Parameters of multi-band power system stabilizer are presented in Table 2.

$$P \quad (s) = K\frac{sT_w}{1 + sT_w}\,\frac{(1 + sT_1)(1 + sT_3)}{1 + sT_w(1 + sT_2)(1 + sT_4)} \quad (4)$$

TABLE.2. PARAMETERS FOR MULTIBAND-PSS

Parameters	Value
Global Gain	1
LF band (Low Frequency)	[0.3 20]
IF band (Intermediate Frequency)	[1.55 30]
HF band (High Frequency)	[10 160]

For the effective damping, multiband power system stabilizer has been developed which works on multiple bands. An elaborated model of IEEE standard 421.5 PSS has been implemented in order to overcome the problem of stability in microgrid system. Parameters of developed multiband stabilizer have presented in Table 2. The implemented stabilize works on low, intermediate and high frequency bands as shown in Fig. 2.

D. Parameters Estimation of Synchronous Generators

The standard parameters of synchronous generator can be calculated through sudden short circuit test and load rejection tests, while the fundamental parameters can be calculated by using mathematical relations. Ref. [25] has estimated the parameters of synchronous generator by using the step voltage response. Synchronous machine parameters have been calculated by by standstill tests in [26].

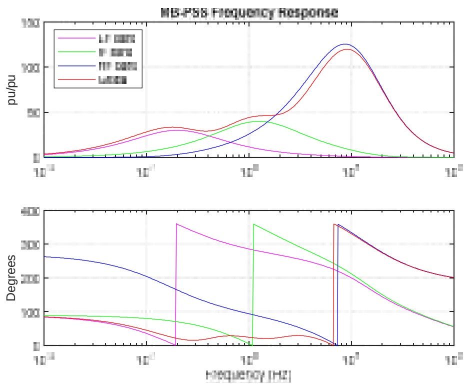

Fig. 2. Frequency response of multi-band power system stabilizer

In the studied microgrid system, the parameters of synchronous generator have been calculated as ANSI-IEEE Std. 115A [27]. The d–q axis equivalent circuits have been developed to estimate the fundamental parameters. Then genetic algorithm has been utilized to optimize the parameters as described in [28]. A three phase short circuit test has been used to check the validity of estimated parameters.

III. VOLTAGE AND FREQUENCY DROOP CONTROL

In microgrid, synchronous generator operates as per the load changes. In case of more load demand, the distributed generators are required to supply more power to meet the load demand. Active power injection is increased in microgrid based on the frequency droop values. Generally, the frequency droop coefficient can be described as.

$$k_p = \frac{Cha \quad o \;\; f_r \qquad n \quad f}{Cha \quad o \;\; p \quad f \quad s \;\; p}$$

$$f = f0 + (P - P0) \qquad (5)$$

Where

P =Active power of system
P_o =Active power reference
K_p = Droop gain
f = System frequency
f_o = Frequency reference

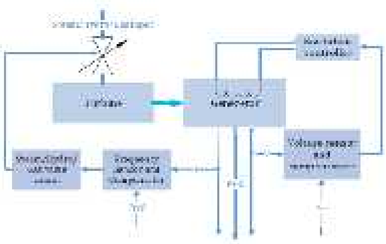

Fig. 2. Load frequency and excitation voltage regulator of a turbo-generator

In case of reactive power drop, the voltage of microgrid drops. In this case, voltage droop is utilized to for voltage stability. The basic voltage droop can be described as.

$$V = V \;\; ri \; + k \;\; (Q - Q0) \qquad (6)$$

Where

Q = Reactive power of system
Q_o = Reactive power reference
Kq =Droop gain
V = Voltage of system
Vo = Voltage reference

A. *Parallel Operation of Generators and Load Sharing*

To avoid the instability and overloading issues in the multiple generators based microgrid proper load sharing of generators is very important. To supply power to common loads, parallel operating generators share active and reactive power in islanded mode. In parallel operating generators, active power sharing varies with the variation in the load angle and the reactive power supply is dependent on the voltage magnitude. In case of multiple operating generators, the portion of supplied power by each generator depends on the frequency droop coefficients. In case of frequency increase or decrease, generators respond and adjust input power to mitigate the frequency change and frequency stability is achieved. In case of voltage increase or decrease, reactive power of generators is adjusted as per the voltage droop coefficients.

B. *Proposed V-F Control Methodology*

At islanding mode of microgrid, it is important to maintain the bus voltage, active and reactive power supply as per the changes in load demand. To do this, a controller should establish a balanced power demand that can provide stable voltage and frequency. Generally, v-f control is implemented to regulate the bus voltage and system frequency at the islanded mode of microgrid. It controls the bus voltage and the system frequency to their pre-defined limits. In this approach, the islanded microgrid is liable to provide the active & reactive power to meet the load demand without utility . This control is usually achieved by changing the values of droop coefficients according to the load demand variations in microgrid [24, 29].

In this approach, the active power is affected by the frequency of system and the voltage is affected by the variation in the reactive power of the system. Active and reactive power regulation is done by changing the droop coefficients values. The droop control can be defined by the following expressions.

$$P_{re} = P_0 + k_p(f - f_0) \qquad (7)$$

$$V_r = V_0 + k_v(Q - Q_0) \qquad (8)$$

K_P and K_v are the constants and are the slopes of the droop characteristics. These values are chosen very carefully as, they impact the stability of the microgrid. Higher values of droop constants can make the load sharing faster, but system stability can be compromised. Smaller values can make the load sharing slow. The slopes of voltage and frequency droop coefficients can be defined as follow.

$$k_p = \frac{(f_r \;\; - f_m \;\;)}{(P_r \;\; - P_m \;\;)} < 0 \tag{9}$$

$$k_v = \frac{(V_r \;\; - V_m \;\;)}{(Q_r \;\; - Q_m \;\;)} < 0 \tag{10}$$

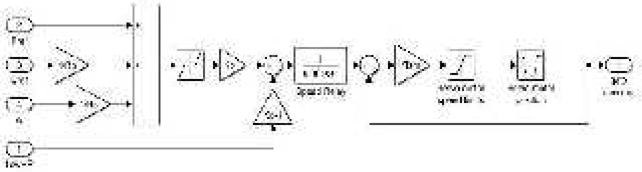

Fig. 3. PI control for speed regulation

Different type of controllers can be used to control the speed of generators [30]. In the proposed scheme, PI controller has been used to monitor and regulate the speed of synchronous generator. By adjusting the load and speed variations, a feedback signal is generated [30], which regulates the frequency. Proposed PI controller has been shown in Fig. 3. It also works as an automatic speed regulator for small microgrid systems. Generally, tunning of PI controller is done by adjusting the proportional and integral coefficient's values manually. In start no integral gain is considered than proportional gain is increased gradually to get the satisfactory response. Then integral gain is added until the steady state error is removed in satisfactory time. Secondly, MATLAB built-in auto tuning can also be used to automatically tune the values of integral and proportional gains. In the proposed approach, both manual and automatic tuning have been used and most satisfactory values have been chosen and applied to the islanded microgrid system.

IV. CASE STUDIES

An islanded microgrid with two parallel operating conventional synchronous generator and loads has been modelled in the MATLAB/Simulink. Two 3-phase, 400 V, 1000 kVA synchronous generators have been integrated with the 5-bus radial distribution system as shown in Fig. 4 and 5. In the proposed approach, P-f , V-Q controller has been implemented with a PI controller for stable operation of IMG. Different load change cases have been carried out to check the stability of the IMG. Following case studies has been performed.

A. Actve and rective power sharing of two synchorous generators.

A base case study has been run at islanded mode. It has been noted that both generators shares equal active & reactive power as presented in Fig. 6. Voltage regulation of microgrid has been presented in Fig. 7. Frequency of system has been established very fast as shown in Fig. 8.

B. Load change scenario

In load change scenario, three loads have been connected to the IMG at 0.7 s, 0.9 s and 1.1 s at buses 3, 2, and 1, respectively. The input data has been given in Table 3. The frequency and active and power changes under this load change scenario has been shown in Fig. 9 and 10 respectively. It has been noted that controllers regulate the microgrid frequency and voltage quickly after the load changes. Frequency also leads to stability after the injection of loads.

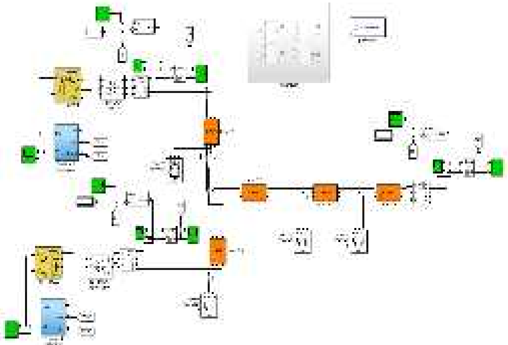

Fig. 4. Modelling of Islanded microgrid

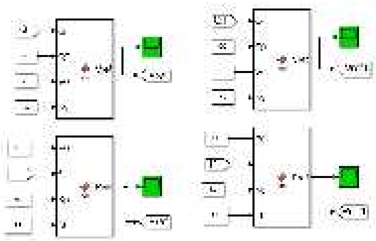

Fig. 5. Voltage and frequency controllers for islanded microgrid

C. Load out Scenario

In load change scenario, two loads have been disconnected from the IMG at 0.5 s and 0.9 s at buses 3 and 4 respectively.

At times 0.5 s and 0.9 s; a load-out change has occurred at buses 4 and 2 respectively. The load change scenario is shown in Table 4. It is noted that frequency and voltage have been stabilized very quickly as shown in Fig. 11 and 12. The active and reactive power sharing also balances itself after the load-out, as shown in Fig.13.

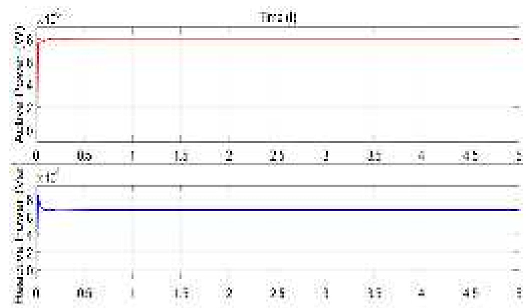

Fig. 6. Microgrid active and reactive power regulation

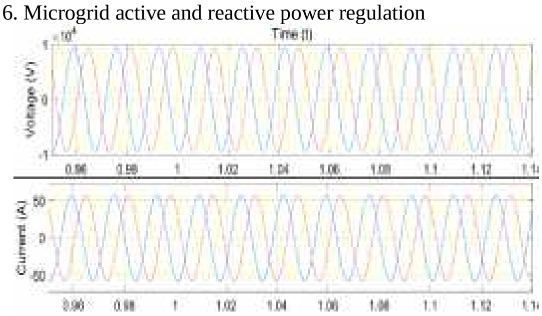

Fig. 7. Voltage stability of two synchorous generators at islanded mode

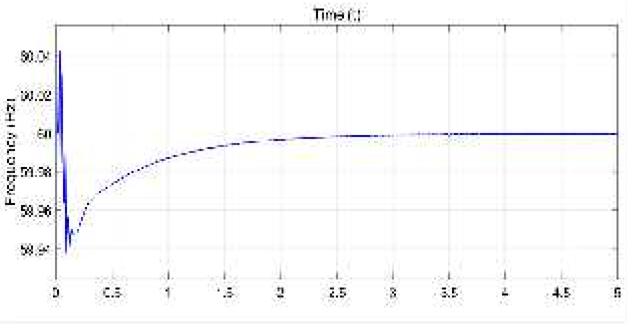

Fig 8. Frequency stability of two synchorous generators

TABLE 3. INPUT DATA FOR CASE 2

Time	Bus Number	Load Change
t=0.7s	3	+50kW
t=0.9s	2	+50kW
T=1.1s	1	+75kW

TABLE 4. . INPUT DATA FOR CASE 2

Time	Bus Number	Load Change
t=0.5s	4	-0.5MW
t=0.7s	2	-0.5MW

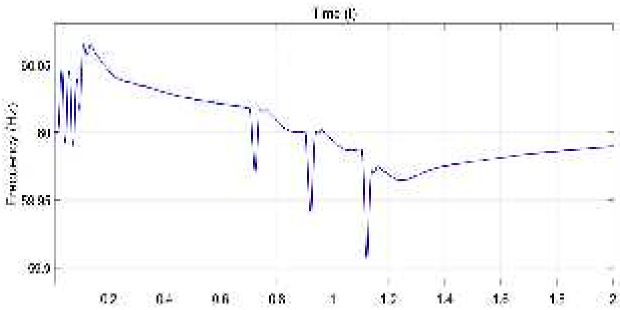

Fig 9. Microgrid Frequency regulation with load changes

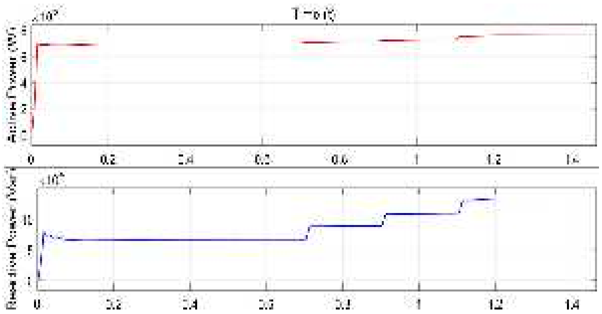

Fig. 10. Microgrid active and reactive power regulation with load changes

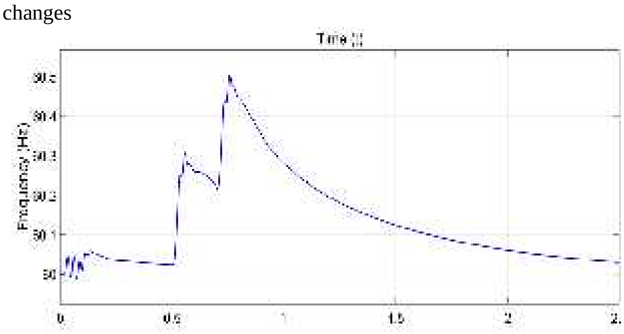

Fig. 11. Microgrid frequency regulation with load out scenario

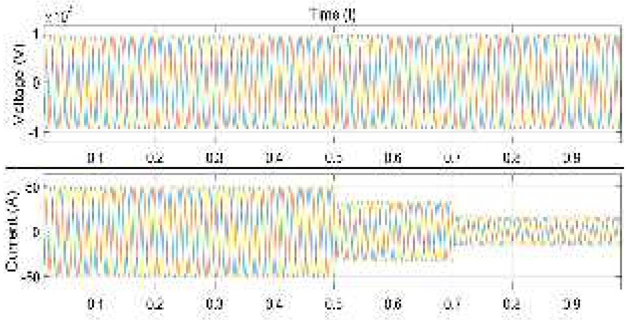

Fig. 12. Microgrid voltage regulation with load out sceniro

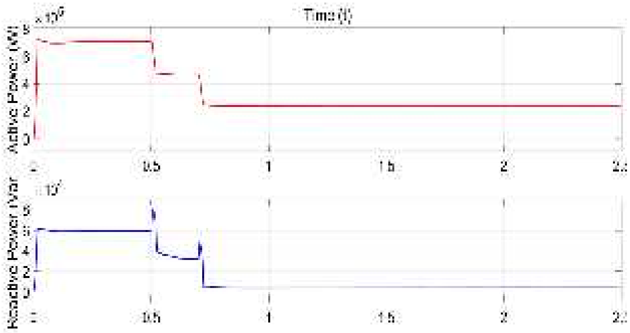

Fig. 13. Microgrid active and reactive power regulation with load out scenario

V. CONCLUSION

This paper has presented a modified droop control based approach with the combination of PI controller for the voltage and frequency regulation of conventional generations based islanded microgrid. The power dispatching of the conventional generator has been studied while considering the voltage and frequency regulation. A 2 MW microgrid system has been modelled at islanded mode. Voltage and frequency controllers have been developed and tested for the base case and load change scenarios. Different case studies have been performed on the developed microgrid. Results and output have proved the strength of the developed approach.

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