Frequency Regulation of Microgrid with Battery Droop Control

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***Abstract*—One of the potential problems with increasing renewable generation in microgrid is frequency regulation. Due to high variability of renewable generation resources, the imbalance between load and generation may lead to instability of the system. Since the microgrid can not compensate the power imbalance from the main grid, demand response in general and battery storage system specifically, can contribute in frequency regulation of microgrid. Conventional generator regulates the frequency with load frequency control (LFC) loop. Batteries connected to inverters can also contribute in regulating the frequency with the embedded frequency-watt control curve in inverter. In this paper, distributed battery storage systems are utilized to correct a given frequency deviation in the microgrid. The battery contribution is analyzed in centralized and decentralized environments. The optimal value of droop of distributed batteries are obtained and the small signal stability of the system is investigated.**

***Keywords*—Battery droop, Frequency regulation, Droop market.**

I. Introduction

Inverter based generation is providing power from distributed resources such as batteries and photovoltaic (PV) cells. Battery energy storage systems can be used to levelise the load curve as well as removing the fluctuations generated by renewables [1]. Although renewable power forecasting [2], [3] plays an important role in managing the available resources, the reliability of system can be improved with extra battery energy reserve. Several control loops have been defined in the inverters so that they can contribute to providing ancillary service to the grid. Frequency regulation is a very important control operation in the power grid which is done by the governor in the generator. However, part of the frequency regulation can be done by the inverters. It is a critical topic in the microgrid stability study especially when it faces some system failures such as islanding condition which happens when DG units within a microgrid continue to energize while the system has been isolated from the main electrical utility. In this situation, if the microgrid continues to operate, it should switch to the stand-alone mode. In this situation it needs to regulate and synchronize the frequency of different generator within the system [4], [5] which should be done after detecting the fault in the network automatically [6], [7]. Frequency regulation in microgrid has been discussed in various papers in the literature. In [8], an adaptive decentralized droop controller for parallel inverter-based DG units is presented. The proposed method which is based on the static droop characteristic, preserves the stability of inverters at different loading conditions. A control method which requires a low-bandwidth communication link is presented in [9] which splits the control tasks in the frequency domain. In [10] a frequency regulation method based on wireless communication is developed. In [11] a model-free generalized droop control scheme fo different load changes is presented. The proposed approach is based on adaptive neuro-fuzzy inference system. A hierarchical control structure is presented in [12] and droop control methods for frequency control in microgrids have been discussed. In [13], [14], frequency regulation reserve using demand response has been discussed in the literature. A demand response market structure is proposed and contribution and pricing of battery participation is analyzed. BESS has been used in [15], to control the frequency at primary level and the optimal size of BESS has been determined. Cooperative frequency control has been discussed in [16]. The power imbalance is shared using average consensus algorithm among the agents using power line carrier. A robust control strategy has been proposed in [17] to cope with frequency changes in microgrid. The proposed approach is compared with conventional PID controller and is shown that has a better performance. A small signal model is used in [18] to investigate the communication delay on the performance of secondary frequency control loop in a microgrid. A review of control techniques for microgrid is presented in [19]. Central and decentralized control methods are discussed and future research opportunities are proposed. Hierarchical control methods for control of active and reactive power are proposed in [20], [21] to share load between different power resources. In [22], a hierarchical frequency control structure is proposed and the frequency dependent control functions are modeled.

II. Frequency control in microgrid

Conventional generators in the microgrids are equipped with Load-Frequency Control (LFC) loops to regulate the frequency. The governor controls the speed of the rotating system by adjusting the amount of input energy to the generator. The governors are designed so that their speed has a linear relationship with frequency, i.e. if the frequency drops the amount of input power ramps up to make up for the frequency change. Also, if the frequency goes up, the input power is reduced to take the frequency to the nominal point. The overall block diagram of LFC loop in the conventional generator is shown in Fig. 1. Parameters τ_g, τ_T and H are governor, turbine and generator inertia time constants. $D\Delta\omega$ and $\Delta\omega$ represent the frequency-sensitive load change and frequency change respectively. The load and reference power change are represented as ΔP_L and $\Delta\omega$. The characteristics of

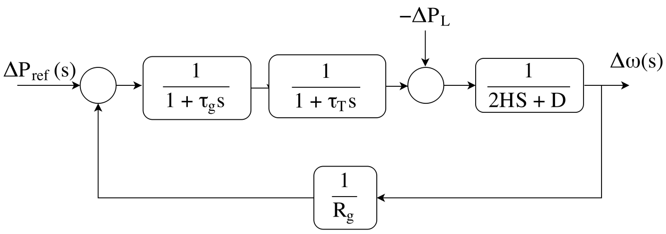

Fig. 1. LFC loop in conventional generator

speed governor is shown in Fig. 2 where the slope of the curve is R_g. The sensitivity of generator to the frequency deviation is given by the slope of the curve. The generator will produce

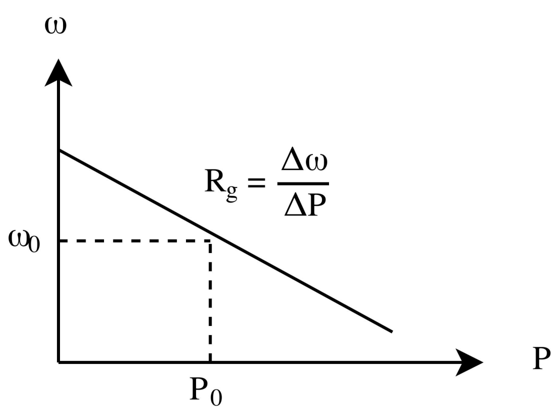

Fig. 2. LFC loop in conventional generator

power P_0 at the nominal frequency ω_0. If there are several generators in the grid, each generator will produce the optimal power based off of an optimal power flow which minimizes the cost of generation considering the power flow constraints. In the next section, we use frequency-watt curves which is integrated in smart inverters. This feature can be employed to regulate the frequency by controlling the power flow of the inverter.

III. Frequency control curve in inverters

Frequency-watt control curve is used to control the frequency by changing the active power output of the inverter. The DC source of inverter can take the energy from renewables such as solar generation. In this case, the output power will be curtailed if the frequency increases above the setpoint. If the frequency drops and there is enough input energy from the DC side, the inverter will ramp up power. If the DC side source of energy is battery, it can either absorb or export power to the grid given the state of charge (SOC) constraints. The proposed frequency-watt curve for battery is given in Fig. 3. In the Sunspec inverter specification, the frequency-watt curve is given for PV inverter. If the frequency of the grid exceeds the triggering point, the output power of inverter is curtailed to regulate the frequency. If the DC side is connected to a battery which can absorb power, we can define the triggering point (c) below the zero power line as shown in Fig. 3. In other words, as the frequency increases, the battery absorbs the extra power to reduce the imbalance between the load and generation. Point (d) can be also defined to reduce the charging power and if the frequency drops more, the battery can discharge to make up for the power deficiency. When the inverter is connected to DC cells, we can either generate or curtail power. Moreover, demand response resources such as water heaters can be turned on to act as loads and absorb the extra power in the grid. When the DC source of inverter is from solar generation, the

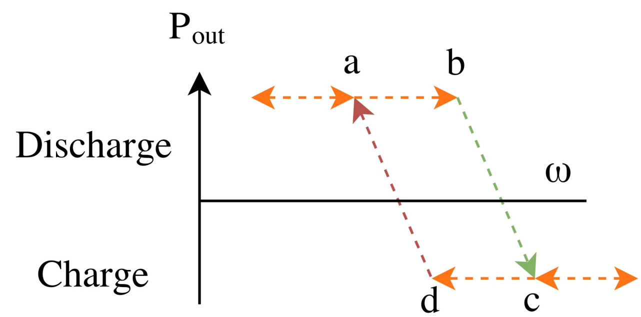

Fig. 3. Proposed Frequency-Watt Curve

power will be curtailed to zero if the frequency passes the nominal point. We can define a dummy load to trigger when the frequency increases which mimics the power absorption of battery.

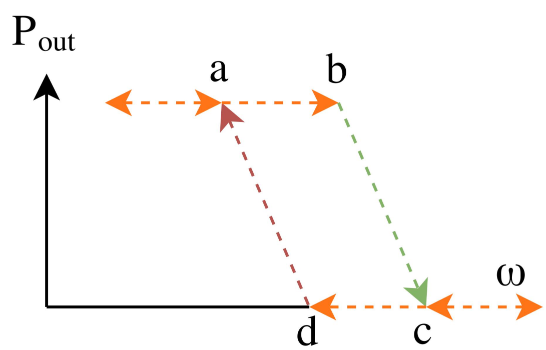

Fig. 4. Frequency-Watt Curve for solar PV generation

IV. Simulation and analysis

After a load perturbation has occurred the frequency changes based on the amount of load unbalance. Part of the frequency deviation can be compensated with battery energy storage systems. Sensitivity of output power of battery can be programmed in the inverter using frequency-watt curve [23].

The battery produces power as the frequency passes the triggering point P3 [23]. The curve can have a hysteresis band in which the battery does not change. A case study in [24] is used to analyze the contribution of battery in correcting the frequency error. The case study is an isolated power station with the following parameters:

$$\begin{aligned} \tau_T &= 0.5sec \\ \tau_g &= 0.2sec \\ H &= 5sec \\ D &= 0.8 \\ P_g &= 250MW \\ R_g &= 0.05 \end{aligned} \tag{1}$$

A sudden load of change of $50MW$ occurs and the frequency deviates from its setpoint of $60Hz$ according to the follwoing relation:

$$\Delta\omega_{ss} = \frac{-\Delta P_L}{D + \frac{1}{R_g} + \frac{1}{R_{inv_1}} + ... + \frac{1}{R_{inv_m}}} \tag{2}$$

Taking into account the change in per unit system, the steady state frequency deviation is calculated from (2):

$$\Delta\omega_{ss} = -0.0096 \ pu = 0.576 \ Hz \tag{3}$$

If the m distributed battery storage systems were to correct $0.1Hz$ or 0.00166 pu of the frequency error, we have:

$$\Delta\omega_{ss} = \frac{-\Delta P_L}{D + \frac{m}{R_{inv}}} = -\frac{0.05}{0.8 + \frac{m}{R_{inv}}} \tag{4}$$

It is assumed that all inverters have the same droop R_{inv}. Solving for the $\frac{m}{R_{inv}}$ in the denomerator of (4), we get:

$$\frac{m}{R_{inv}} = 29.3 \tag{5}$$

The maximum power of a sample battery inverter is $2\,kW$, therefore the droop of battery inverter is:

$$R_{inv} = \frac{\Delta\omega}{\Delta P} = \frac{0.00166}{8 \times 10^{-6}} = 207.5 \tag{6}$$

The droop is provided with the available battery inverters. Plugging (6) into (5) gives the number of required battery storage systems to provide the given frequency correction:

$$m = 29.3 \times 207.5 = 6080 \tag{7}$$

Therefore 6080 inverters are needed to correct $0.1Hz$ frequency error on the system.

V. Small Signal Stability

The overall block diagram of the system with m battery inverterrs is shown in Fig. 5. Since the power contribution of each battery inverter is $\Delta\omega/R$, the overall impact of battery power are added together.

The closed-loop transfer function with load change as the input and the frequency change as the output is shown in the following figure:

The closed-loop transfer function is found as:

$$\frac{\Delta\Omega}{-\Delta P_L} = \frac{(1+\tau_g s)(1+\tau_T s)}{(2Hs+D)(1+\tau_g s)(1+\tau_T s) + (\sum_{k=1}^{m} \frac{1}{R_{inv_k}} + \frac{1}{R_g})} \tag{8}$$

The steady state frequency deviation is:

$$\Delta\omega = lim_{s\to 0} \frac{-\Delta P_L}{D + (\sum_{k=1}^{m} \frac{1}{R_{inv_k}} + \frac{1}{R_g})} \tag{9}$$

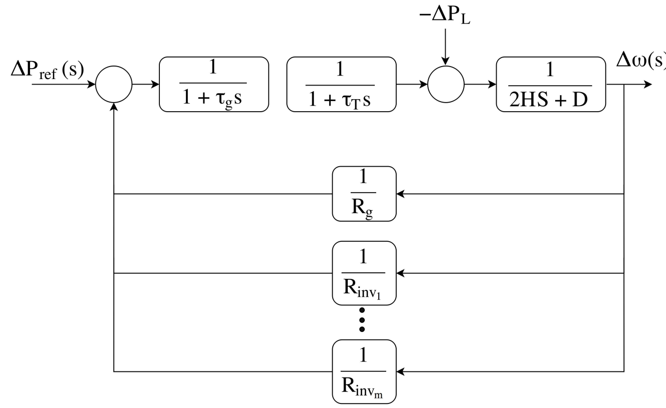

Fig. 5. LFC loop with distributed battery droops

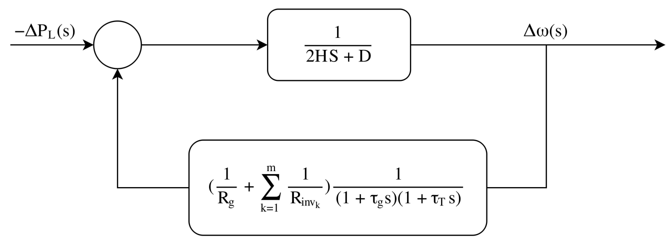

Fig. 6. Closed-loop transfer function

To find the range of battery droop by which the system remains stable, the root locus of the system is plotted here: The system would be stable for the following condition:

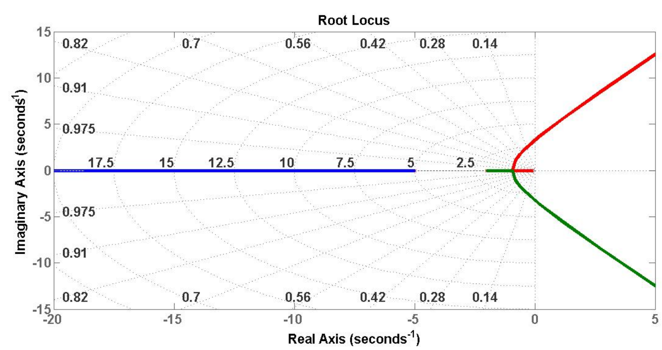

Fig. 7. Root locus plot

$$\sum_{k=1}^{m} \frac{1}{R_{inv_k}} + \frac{1}{R_g} < 73.965 \tag{10}$$

Assuming the value of R_g as 0.05, the range of stability for the inverter droops is:

$$\sum_{k=1}^{m} \frac{1}{R_{inv_k}} < 53.965 \tag{11}$$

If all of the inverters have the same droop, the stability condition from (5) is satisfied:

$$\frac{m}{R_{inv_k}} = 29.3 < 53.965 \tag{12}$$

The maximum number of batteries for a stable system can be calculated from (12):

$$\frac{m}{R_{inv_k}} = \frac{m}{207.5} = 53.965 \tag{13}$$

$$m = 11198 \tag{14}$$

Therefore the microgrid remains stable with maximum number of 11198 battery inverters. In the next section, droop control is studied in a decentralized environment where an aggregate of batteries bid on amount of droop for frequency regulation.

VI. Droop Market

If part of frequency control is managed in a market environment, battery inverters can bid amount of droop they can provide to regulate the frequency. The market is formed of a game with incomplete information and we are looking for Bayesian Nash Equilibrium [25]. The Bayesian game between the droop providers consists of the following items:
A set of battery inverters which participate in the market: I
A set of actions for each player *i*: $\alpha_i \in A_i$
A set of types for each player *i*: $\theta_i \in \Theta_i$
A payoff function for each player *i*: $u_i(s_1, ..., s_I, \theta_1, ..., \theta_I)$
A probability distribution $p(\theta_1, ..., \theta_I)$ over types
The strategy $s(.)$ is a Bayesian Nash equilibrium if for all $i \in I$ and for all $\theta_i \in \Theta_i$, we have

$$s_i(.) \in \underset{s'_i \in S_i}{\text{argmax}}\{\sum_{\theta_{-i}} p(\theta_{-i}|\theta_i) u_i(s'(i), s_{-i}(\theta_{-i}), \theta_i, \theta_{-i})\}$$

$$\theta_{-i} = (\theta_1, ..., \theta_{i-1}, \theta_{i+1}, ..., \theta_l) \tag{15}$$

Each player in the market, whether an aggregator or an individual household equipped with battery inverter will bid on amount of droop response for frequency regulation. The distribution system independent operator (DSIO) will collect the bids and clear the market. Clearing market not only considers the financial aspects of the bids but also reliability of the system. In other words, if the bids endanger the stability of the system, they will be rejected. Each perticipant will be informed of the results ech time step ahead. The time step is usually about 15 minutes so that the amount of uncertainty in state of charge of batteries remains pretty low. Therefore, th batteries can provide the amount they have offered in the frequency regulation market.
Suppose two parties are offering two droop values whose sume will satisfy the stability constaints in (11). Let's assume that supply curve is an affine function of the following form:

$$P(R) = \alpha - R \tag{16}$$

where R is the quantity of reciprocal of droop that market participants offer for sale. Assume that two players are offering two droop qantities. Player number 1 has only one type wwhereas palyer number 2 has two types, low and high, meaning that it could either bid low or high in the market. The playes can have an infinite number of types and as a result the summation in (15) chnages to integral in this state. The payoff fot the two players is given as below:

$$u_1 = r_1(P(r_1 + r_2) - C)$$
$$u_2 = r_2(P(r_1 + r_2) - C_k), \quad k \in \{L, H\} \tag{17}$$

where r_1 and r_2 ae the reciprocal of droop values of the batteries. The equilibria responses are given by solving the following set of equations:

$$\frac{dB_t}{dr_t} = 0 \quad t \in \{1, L, H\} \tag{18}$$

where B_t is given as:

$$B_1 = \theta(P(r_1 + r_2) - C)r_1 + (1 - \theta)(P(r_1 + r_h) - C)$$
$$B_L = (P(r_1 + r_L) - C_L)r_L \tag{19}$$
$$B_H = (P(r_1 + r_H) - C_H)r_H$$

Solving for the equiliberia, we get:

$$r_1^* = \frac{1}{3}(\alpha - 2C + \theta C_L + (1 - \theta)C_H)$$
$$r_L^* = \frac{1}{3}(\alpha - 2C_L + C - \frac{1}{6}(1 - \theta)(C_H - C_L))$$
$$r_H^* = \frac{1}{3}(\alpha - 2C_H + C - \frac{1}{6}\theta(C_H - C_L)) \tag{20}$$

As the paticipant 1 puts more weight on the probability that participant 2 is of L type, the amount of droop will gear more towrads the cost of C_L. Conversely, if type 2 has a higher probability, then the amount offered by participant 1 will be affacted more by C_H. The same conclusion can be applied to participant 2 for two types of L and H.

VII. Conclusion

In this paper, battery droops are used to compensate part of frequency deviation in a microgrid with a conventional generator. The conventional generator is equipped with LFC loop which regulates the frequency. Although the generator can regulate the frequency without contribution of distributed battery storage systems, battery power can replace some power imbalance in the grid. A given part of frequency deviation is corrected with contribution of distributed battery storage system across the grid. This value can be changed based off of economic optimization between battery stoarge systems and conventional generator. As the penetration of distributed resources increases, battery storage systems can have a higher contribution in regulating the frequency. The power of batteries are used to compensate for a small portion of frequency deviation and the stability region of battery droops is calculated. Based on the stability margin, the maximum number of battery storage systems are calculated. This number will lead to marginal stability of the system.

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