Microgrid Primary Control And Continuous-Time Operation

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***Abstract*—This paper details the primary control of a microgrid in islanded mode of operation. More specifically, specific droop control curve settings are developed for the energy storage system acting as the isochronous resource to maintain a desired state of charge for sufficient reserve for future provisions, as well as a means to instantaneously request more or less power from other distributed resources without using the communication infrastructure.**

Keywords—microgrid; distributed energy resource (DER); electrical storage systems (ESS); state of charge (SOC).

I. INTRODUCTION

The difficulties of integrating a high penetration of DER as well as optimizing system operation give rise to the need for coordinated control amongst available DER. This can be implemented through a microgrid, which some have argued is a crucial element in the power systems to help resolve the problems associated with the integration of DER [1]. Energy storage systems (ESS) or controllable loads have been studied and implemented in microgrids to aid in mitigating some of the adverse effects arisen from the volatile nature of renewable energy sources. For example, ESSs have been shown to aid in the integration of RED through power smoothing [2, 3], cost minimization [4], generation shifting [5, 6] or providing ancillary services such as frequency regulation [7].

This paper proposes a microgrid primary control strategy, specifically designed for the islanded mode of operation. By using the ESS as the isochronous resource, the frequency droop when in islanded mode allows the SOC to be maintained within desired levels to mitigate any intra-dispatch power fluctuations with uncontrollable resources while instantaneously requesting more power from other DER's droop curves. The novel approach to the storage system's isochronous controls addresses its power and energy limitations by modifying the systems frequency independently from its power output to "request" more or less power from other DERs through their droop curve settings without requiring the communication infrastructure. The ESS' power and energy droop curves for frequency ensures that an optimal SOC is maintained for any future event while its power limits are satisfied. Not only must the power be balanced when a microgrid operates in islanded mode, but it is imperative that the voltage and frequency need to be maintained within acceptable operating limits [8]. This is typically achieved by a single distributed energy resource (DER) operating in isochronous control mode, while the other DERs operate in droop control mode. The chosen isochronous DER is responsible for regulating the frequency and the voltage in the microgrid by acting as a slack unit to increase or decrease its power output as the load or other DERs' powers change.

II. ENERGY STORAGE SYSTEM ISOCHRONOUS CONTROL STRATEGY

An electrical storage system (ESS) is an appropriate DER to be used as the isochronous resource since it is a flexible and fast-responding resource that can either act as a generator or a load, and it can set the frequency through its power electronic controls, thus taking the responsibility of being grid former. An ESS has been used as the isochronous resource in the ESS-photovoltaic microgrid in Kythnos Island, Greece [17]. However, the main limitations of ESS' ability to act as the isochronous DER are not only its power rating, but also the energy rating and its state of charge (SOC). For example, if the SOC is too low, and a large load comes online, the ESS may not be able to balance the power after its energy reserves have been depleted.

The Kythnos microgrid addresses this issue by actively modifying the frequency if the SOC becomes too low or too high [17]. If the SOC is too low, it forces the frequency to decrease in order to signalize the need to shed some loads, to allow the ESS to charge towards central levels. If the SOC is too high, it forces the frequency to increase to signal to the photovoltaic generators to curtail its generation to allow the ESS to discharge downto a central level. Although this method has been shown to be very effective, it only acts in extreme situations with extreme SOCs, thus reducing the energy delivered to the customers and the renewable distributed generation (DGs') capacity factor. Furthermore, the power rating of the ESS must be sufficiently large to be able to deliver power to the entire load and absorb the peak power from the generation.

III. PROPOSED ISOCHRONOUS CONTROLLER DESIGN

A more appropriate implementation would take into consideration both the power and energy limitations. The principle behind the proposed approach is to accommodate the ESS' shortfalls of a limited energy capacity, variable SOC, and constrained power rating limit. Much like the other droop-

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based controls [11, 12, 13, 14, 15], this implementation does not rely on any communication infrastructure to request additional or reduced power from the other DERs in the microgrid to enable a fast response from their respective primary controllers. Two independent droop curves are formulated for the two ESS' characteristics: the SOC and the power rating.

The SOC limits the ability of the ESS to maintain power balance in any situation, especially on long term unbalances, in order to prevent the ESS from either depleting its reserve or reaching capacity. The microgrid control based on battery availabe energy (indirectly described by SOC) can impose a droop curve based on the idea of operating the ESS close to the desired SOC, e^*_{ESS}. In order to maintain continuous operation in the microgrid, the desired SOC for the isochronous ESS must fulfil two roles, as described in subsequent paragraphs.

First, the ESS must support the microgrid's ability to maintain an island for a long, unknown duration. To determine this desired SOC, an analysis of the residual power $P_{res}(P_{res} = P_L - P_W - P_S)$ over the previous year is analyzed, where P_L is the load power, P_W is the wind-based power generation and P_S is the sun-based power generation). For every time period t, the SOC is analyzed to determine the duration the ESS can help supporting the microgrid (based on the available SOC from 0-100% in 10% increments) starting from that time t_0. Based on the load, wind, and solar profiles from [16], the average duration (Tsup) that the ESS can support the island based on its initial SOC is shown in Figure 1. Based on a 100% renewables penetration in this study (e.g. 50% solar and 50% wind), the SOC should be at 100% in order to achieve the highest probability of maintaining a sustained island if there is temporary lack of renewable production.

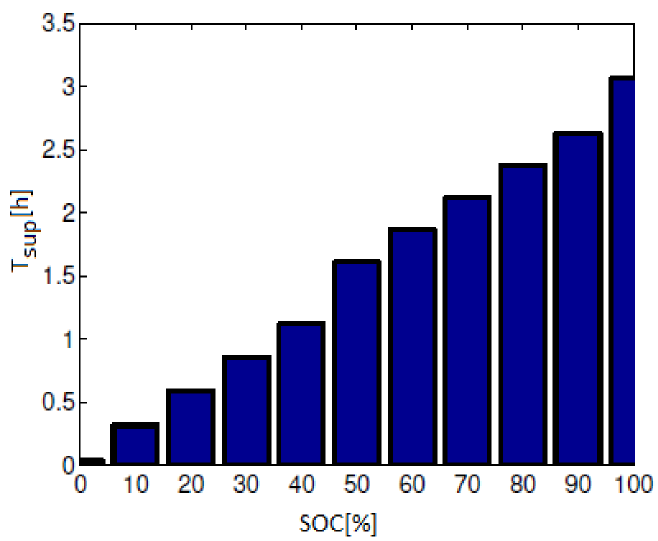

Fig. 1. The average duration that the ESS can support the full islanded microgrid consumption versus its initial SOC.

Second, the ESS must mitigate any instantaneous power fluctuations, in case of e a large increase or decrease of either load or generation in order to maintain power balance. This desired SOC is set to 50% to have an equal ability to respond to a positive or negative power fluctuation. The final desired SOC is taken as the average of the desired SOCs for the two requirements:

$$e^*_{ESS} = \frac{1+0,5}{2} E_{ESS} = 0,75 \cdot E_{ESS} \quad (1)$$

As our study relates mostly to [8], our further analysis points also on a 60 Hz nominal frequency, however the findings are applicable to 50 Hz networks as well. The energy droop curve is formulated to operate at nominal frequency (f_{nom} = 60 Hz) when it is at its optimal SOC (0.75 ESS in our case), the minimum allowable frequency ($f_{\min}$ = 59.3 Hz) when the SOC is at 0%, and the maximum allowable frequency ($f_{\max}$ = 60.5 Hz) when the SOC is at 100% (as defined by DG interconnection standards [8]). Therefore, two linear regions (to the left and right of the desired SOC) are formulated, and the resulting energy droop curves are provided in (2), and is shown in Figure 2. By allowing the ESS to maintain or operate to achieve a certain SOC during normal operation, no generation needs to be curtailed and no loads need to be shed.

$$f = \begin{cases} \dfrac{f_{nom} - f_{\min}}{e^*_{ESS}} e_{ESS} + f_{\min} & if\ e_{ESS} \le e^*_{ESS} \\ \dfrac{f_{\max} - f_{nom}}{1 - e^*_{ESS}} e_{ESS} + \dfrac{f_{nom} - e^*_{ESS} f_{\max}}{1 - e^*_{ESS}} & if\ e_{ESS} > e^*_{ESS} \end{cases} \quad (2)$$

Since the ESS is coupled to the microgrid through power electronics, it does not have inertial tendency to reduce/increase the frequency if the power requirement is too high/low through its inertial rotating mass. In other words, they can be decoupled and the frequency can be set as a parameter that is not bound by the ESS' power output. Therefore, should the power requirement of the ESS deviate to a level that approaches its limit, the ESS is able to change the power outputs of other DER by changing the reference frequency, thus modifying the operating point on other DERs' respective power droop curve.

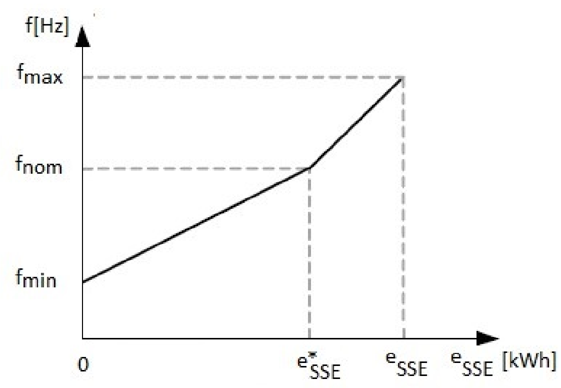

Fig. 2. ESS' energy droop curve in isochronous mode, defined by (2).

One of the principles of having an isochronous DER is that it should effectively act as a slack resource that can handle any sudden power fluctuation. As such, if the power fluctuation is within 80% of the power rating of the ESS (noted below as

p_{ESS}), there is no need to modify the frequency of the system as the ESS can manage such a change by itself. However, if there is a large power fluctuation that requires the ESS to charge/discharge greater than 90% of its power rating, the ESS immediately modifies the microgrid's frequency to have the other DER modify their power outputs to maintain power balance. A new equilibrium is met at a new frequency as the power sharing matches the load power. If this were implemented in a microgrid, the power would either return to normal (as this could have been caused by a fluctuation with renewable DG sources), or a new dispatch would be set by the microgrid's secondary controller. This is shown in Figure 3 with the dead band between $p_{ESS} \in [-0{,}8P_{ESS}, 0{,}8P_{ESS}]$ and the equation for the power droop curve is given in (3)

$$f = \begin{cases} \dfrac{f_{nom} - f_{\max}}{0{,}2P_{ESS}} p_{ESS} + 5f_{nom} - 4f_{\max} & \text{if } p_{ESS} \leq -0{,}8P_{ESS} \\ 60 & \text{if } -0{,}8P_{ESS} < p_{ESS} < -0{,}8P_{ESS} \\ \dfrac{f_{\min} - f_{nom}}{0{,}2P_{ESS}} p_{ESS} + 5f_{nom} - 4f_{\min} & \text{if } p_{ESS} > 0{,}8P_{ESS} \end{cases} \quad (3)$$

The overall droop curve used is dependent on both the power and energy rating; however, a priority is used for the power droop since the short-term power fluctuations from renewable DGs or loads can cause balancing issues that must be dealt with immediately. Therefore, if the power output of the ESS is within 80% of the power rating (regardless of charging or discharging), then the ESS will use the energy droop curve; otherwise, it will use the power droop curve as this becomes the most pressing limit.

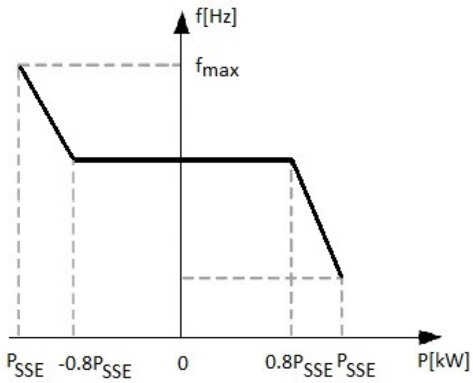

Fig. 3. ESS' power droop curve in isochronous mode, defined by (3).

An overview of the implementation of the controls is shown in Figure 4 where EPS is the Electrical Power System if the microgrid is grid connected, Vd and Vq are components of the Park transformation, abc/dq0 and dq0/abc are Matlab/Simulink direct and reverse Park transformations and blocks (2) and (3) implement above formulas (2) and (3).

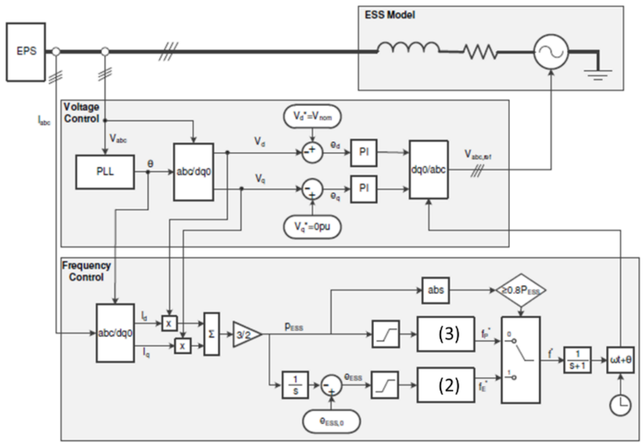

Fig. 4. ESS' voltage and frequency controls for the VSC model.

IV. System Overview

This isochronous control scheme is implemented on an ESS operating in voltage-frequency control mode. The single line diagram of the system, comprising the ESS, two DGs and resistive loads, is depicted in Figure 5. The ESS is modelled as a voltage source as it is operating in voltage control mode for the islanded microgrid.

The ESS' energy rating is particularly low in these test cases to show the effects of the SOC changing during the simulation time.

The DG resources are modelled as a current source in current control mode that follows the reference voltage of the microgrid as measured at their respective point of common cupling (PCCs). The slope of the droop curve of the DGs are determined through the respective economic marginal cost curves to ensure an economic operation of the DGs as the frequency deviates from its nominal point.

The loads are modelled as simple passive resistive loads, and power fluctuations in the system are implemented through loads suddenly coming online or offline. The system simulation is implemented in Matlab/Simulink, and the microgrid is represented in a simplified manner, with all elements connected to a common busbar, and is only operating in islanded mode for all test cases.

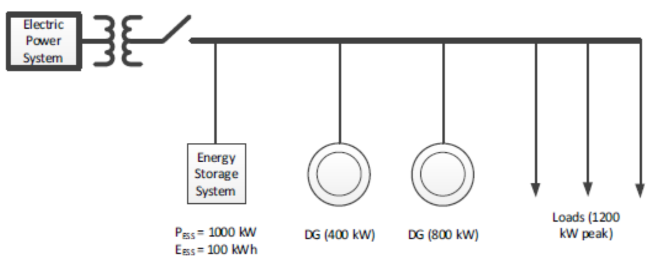

Fig. 5. Single line diagram of the islanded microgrid.

V. RESULTS

Four test cases are structured to demonstrate four different operating conditions, within a scenario considering p_{ESS} =1000 kW and E_{ESS} = 100 kWh.

1) SOC is low: The SOC is initialized at 45%, which causes the frequency of the output voltage to initially be 59.8 Hz, as for this status applies equation (2). As the DGs' respective power outputs have increased with this lower frequency, the ESS' SOC slowly increases as it charges toward the desired 75% SOC. As shown in Figure 6, a negative p_{ESS} indicates that the ESS is charging. At times t = 2 s and t = 4 s, the load suddenly changes with ΔPL = 800 kW, although the ESS is able to modify its power output to maintain power balance and the voltage magnitudes remain constant. Since the charging power of the ESS has in this case a small negative value during the interval t = [2 s, 4 s], the ESS' SOC does not change significantly and so the frequency remains relatively constant. Therefore, the energy droop curve (2) is employed and the microgird is able to charge the ESS towards its desired SOC even under a change in load.

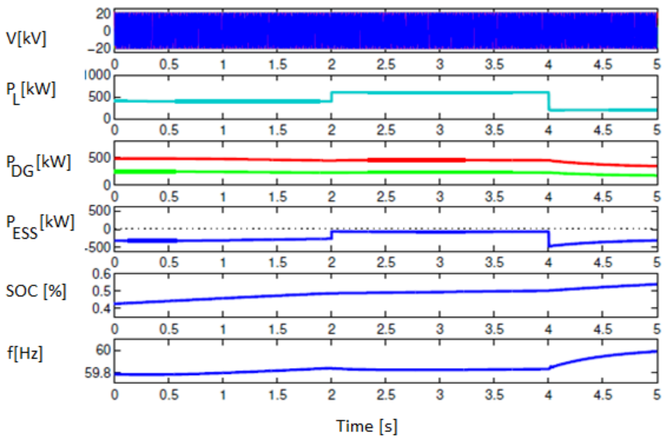

Fig. 6. Time-based measurements of the microgrid when the ESS' SOC is low.

2) SOC is high: The SOC is initialized to 80%, which causes the frequency of the output voltage to initially be 60.17 Hz. The equation (2) apply as well in this situation, as the p_{ESS} is still within the ±80% boundaries. Similar to the analysis made to the case with the low SOC, the higher frequency causes the other DGs to reduce their power outputs due to their frequency droop control mentioned above, so the ESS is able to discharge its stored energy to get closer to its desired SOC of 75%. As is shown in Figure 7 after the load is increased at t = 2 s, the power output steadily decreases as the SOC discharges its power and gets closer to the desired SOC, and the power balance is maintained by increasing the other DG's power outputs.

3) Large negative power fluctuation: In this test case, the load decreases suddenly at t = 1 s (which can also represent a sudden power increase from a renewable DG), which causes the ESS to drastically decrease its power output to maintain power balance. To demonstrate the ESS' ability to switch from the energy droop to the power droop curves, the worst-case scenario is used where the ESS' SOC is high (slightly under 80% in this case, thus, it wishes to discharge according to equation (2)), but it is required to charge to maintain power balance under the new operating condition, when $|p_{ESS}|$ exceeds 80%, thus asking for prioritized operation based on power droop described by equiation (3). During the power fluctuation that is shown in Figure 8, the ESS' SOC increases, but the power output from the other DGs increases to share the burden of the power fluctuation so that the ESS does not charge to its capacity. After the load power increases, the ESS returns to the energy droop control so that it can continue to discharge.

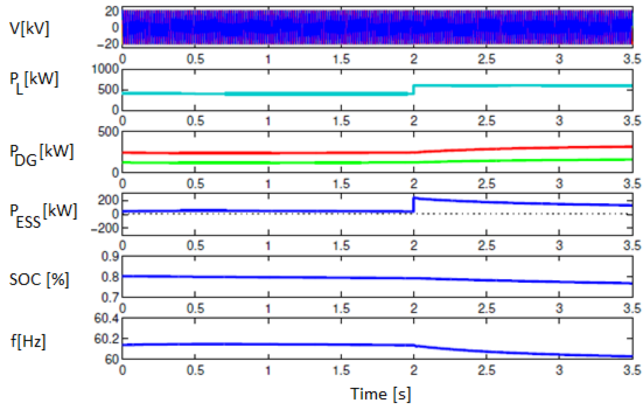

Fig. 7. Time-based measurements of the microgrid when the ESS' SOC is high.

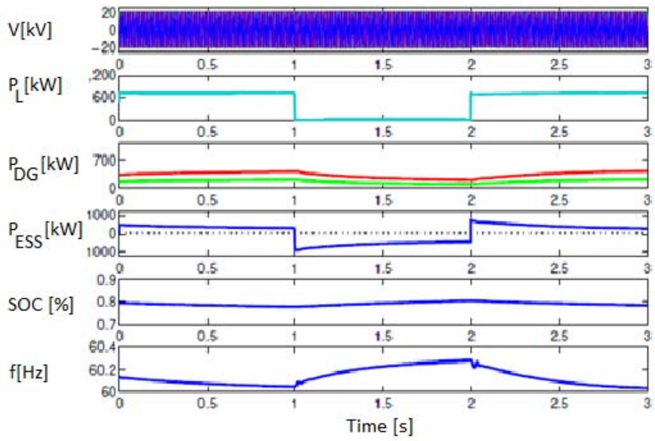

Fig. 8. Time-based measurements of the microgrid when the ESS' power is low.

4) Large positive power fluctuation. In this test case, the load increases suddenly (which can also represent a sudden power decrease by a renewable DG), which causes the ESS to drastically increase its power output to maintain power balance. The worstcase scenario is also used where the ESS' SOC is low (thus, it wishes to charge), but it is required to discharge to maintain power balance under the new operating condition. During the power fluctuation that is shown at time *t* = 1s in Figure 9, the ESS goes from charging to discharging as the load suddenly increases, despite the fact that the SOC is lower than its desired SOC. At time t = 2s in Figure 9, the power decreases to the point where the power droop curve becomes the limiting factor; although both the energy and power droop curves wish to charge the ESS. Therefore, the control scheme of the dual droop curves based on the ESS' SOC and power output have been shown to be an effective isochronous strategy for the ESS to maintain power balance in an islanded microgrid.

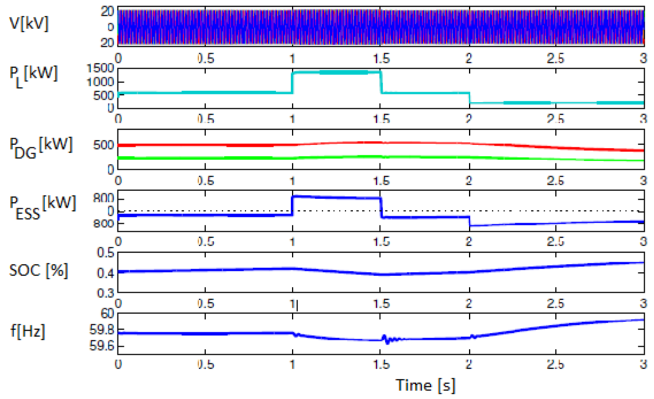

Fig. 9. Time-based measurements of the microgrid when ESS' power is high.

VI. Conclusions

The paper presents a novel strategy for an ESS to operate as an isochronous DER while considering its power and energy limitations. The formulated dual droop curves enable power sharing of the DER in the microgrid, and the strategy of selecting the appropriate droop curve based on the immediate limiting factor has been proven to be effective in maintaining the voltage and frequency within nominal operating limits and maintaining power balance. The effect of implementing a desired SOC enables the ESS to manage any power fluctuation should the microgrid incorporate any volatile resources, such as renewable DGs or variable loads. This has been demonstrated with simulations in four representative situations. Further implications of this strategy includes the ability for other DER to easily implement load shedding or DG curtailing techniques to help maintain power balance in extreme circumstances. This implementation ensures that the ESS maintains sufficient charge for any variation in load or generation power, which is best applied for microgrids that contain highly volatile renewable generation, such as wind and solar generation.This work is also applicable for remote communities whose electrical systems are effectively operation as permanently islanded systems [17].

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