Energy Balance in AC Is-landed Micro-grid by Frequency Bus Signaling Method

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Abstract - *To keep the frequency stable and maintain overall stability of the AC Is-landed micro-grid, power exchange among DGs, ESS, and loads should be balanced. Many innovative control techniques have been proposed and used for enhancing the stability of micro-grid for proper energy balance. In this work, a self-Governing autonomous power control strategy based on Frequency Bus signaling is proposed in order to achieve power management. The main objective of this proposed strategy is to control the state of charge of Battery reservoir limiting the voltage on its terminals by controlling the power generated by the Renewable energy sources. The electrical frequency of the micro-grid is used to inform the power sources and their respective converters the amount of power they need to generate in order to maintain the ESS state of charge below or equal its maximum allowable limit. This method uses only local measurements for power distribution. Main power management function is implemented locally in primary level, while bounded frequency control can be achieved by using additional controller system.*

Key Words: **Energy Storage Systems (ESS), Renewable Energy Sources (RES), Distributed Generation (DG), Distributed Storage (DS), Pulse Width Modulation Converters.**

1. INTRODUCTION

We are observing extraordinary growth and challenges in power generation, transmission and usage. New technologies include power generation from renewable energy (RE) resources. Renewable energy generation sources often come in the form of tailored distributed generation (DG) systems in grid-connected or standalone configuration [5]. Power electronics plays vital role to achieve this revolutionary technology. Future grid will be number of interconnected micro-grids in which every user is responsible for the generation and storage part of the energy. Hence, micro-grids are major elements to integrate renewable/distributed energy resources as well as distributed energy storage systems.

Now, technocrats have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated together into the grid. With this idea, whole energy system will be more efficient, intelligent, and wide-distributed. The use of distributed generation (DG) makes no sense without using distributed storage (DS) systems to cope with energy balances. [2]. Technological advancement in power electronics has led to a condition where renewable energy sources can be virtually considered as completely controllable, within the limits imposed by natural phenomenon. Also, it was envisaged that a large-scale integration of new technologies into a smart grid (SG) will be quite critical if it is done independently. Thus, an idea of merging small variable nature sources with energy storage system (ESS) into a singular controllable entity that can work independently or grid-connected brought to a Micro-grid (MG) concept [3].

In an islanded operation of micro-grid having few micro-sources, the local frequency and the voltage control is not straightforward. During is-landing, the power balance between supply and demand does not match. As a result, the frequency and the voltage of the micro-grid will fluctuate, and the system can experience a blackout unless there is an adequate power-balance matching process. The frequency of the micro-grid may change rapidly due to the low inertia present; hence frequency control at local level is one of the main issues in islanded operation. The ESS is based on power electronic device and has a very fast response time. Therefore, a properly designed ESS can allow a system to stabilize by absorbing and injecting instantaneous power. [6]

Extracting all available maximum power from RESs (MPPT) is desirable, but not always appropriate in isolated systems, as it can lead to an unmanageable excess of energy, resulting in possible overcharging of ESS. On the other hand, a battery, an ESS has specific requirements for recharging to obtain optimum life. So, there should be an option to control the units in the system according to their specific features as well [3].

In is-landed micro-grid comprised of the ESS and PV generation, the ESS unit is usually operated as a grid forming unit that regulates ac bus, while the PV systems work as grid feeding units that inject all available power into the system. ESS plays an important role for achieving the goal of power balance and grid frequency support in a safe range of state of charge (SOC). However, this active power regulation strategy will make SOC out of safe control region if imbalance between consumption and generation lasts longer. These situations are referred to as overcharge and over discharge conditions, and it is well known that they may bring permanent damage to the ESS. On the other hand, auto power regulation of the ESS to maintain it within the SoC limits with ignoring the imbalance of power generation & consumption will deteriorate the frequency regulation function. Hence, the coordinated active power control strategy should take into account status of all micro-grid elements such as the SOC of ESS, power available from the PV systems, and demand of power consumption.

2. ENERGY BALANCE TECHNIQUES

Many techniques have been proposed for coordination of RES and ESS in ac & dc standalone systems. Some of them are based on central supervisory controller with enabled communication interface to every unit. Although, it offers the best control capability, the reliability of this is low as its proper operation relies on a single component. Also, with an increase in the number of units, their connectivity may require extensive hardware. Most popular cooperative control strategy of micro-sources and ESS is based on centralized two layered control structure [6] wherein ESS handles frequency and voltage as a primary control and then secondary control in micro-grid management system returns the current power output of the ESS into zero. The ESS absorbs or injects the power through the droop characteristic and the frequency deviation is removed by automatic generation control (AGC) of supervisory controller. Due to limited data that it can process and inherent single point of failure, this method can be implemented in concentrated systems only [6]. There is an alternative strategy i.e. modified droop control strategy to control the generated power within an isolated micro-grid with distributed RES [3]. It is to control the terminal voltage of the existing battery banks below or equal its maximum allowable value. This is done by limiting the amount of power that each energy source can generate at each instant using a modified droop control strategy [3]. But, switching actions of droop curve may trigger stability problems induced by sudden bus frequency changes in micro-grid.

In Co-ordinated control strategy, each unit can operate in different operation modes taking into account the resource limitation [10]. By introducing a Primary-Frequency-Signaling (PFS), coordinated control between units is realized. An interesting way of communication is suggested using the information of AC bus for coordinated operation. Bus signaling concept can be utilized with bus frequency deviation as primary frequency signaling (PFS) to enable system achieving source scheduling automatically. Co-ordinated control based on PFS requires each unit to be capable to regulate output frequency based on its source condition and output power. The PFS principle is introduced to achieve the coordinated control without communication link. Then control strategy based on droop method and virtual impedance can be implemented [10].However, when no. of DGs increases, it becomes difficult to determine the bus voltage/frequency threshold.

Subsequently, Power Line Signaling method which is a distributed control strategy [7] in which the units inject sinusoidal signals of specific frequency into the common bus in order to communicate with each other was proposed. To achieve a zero steady-state error of injected signals in the common bus, primary control of batteries has been extended with dedicated proportional-resonant controllers that are switched ON only during injection period. As the main focus for PLC is data transmission, frequencies from a few kilo-hertz up to several hundred mega-hertz have been used achieve acceptable physical layer rate. Here, the power lines are used as a carrier of sinusoidal logic signals only. The advantage is that instead of having fixed voltage deviation through-out the particular operating mode, PLS signals are used as triggers for mode transitions where deviation can be alternatively cancelled by secondary control action without affecting proper operation. The multiple resonant frequencies of these signals should be properly designed to avoid overlapping, and the coordinated signals may introduce noises into the distributed units [7].

Recently, an autonomous active and reactive power distribution strategy [9] that can be applied directly on current control mode (CCM) inverters, being compatible as well with conventional droop-controlled voltage control mode (VCM) converters is proposed wherein active power distribution is based on unified local control algorithm which ignores the inherent power regulation difference between ESS and RES.

To ensure efficient utilization of PV, to avoid Over-charge and over-discharge conditions of ESS by keeping SOC of ESS in a safe range, to deliver constant power to load at any point of time with adequate power from PV, to prioritize the load to avoid voltage instability, to ensue frequency stability by ensuring power exchange balance among DG, ESS and load, to maintain system Energy balance without using dump loads and to avoid sudden bus frequency changes, self-governing autonomous power control strategy based on Frequency Bus Signaling is suggested.

3. SYSTEM DESCRIPTION

In this study, self-governing autonomous power control strategy compatible with a hierarchical control scheme is proposed for islanded ac micro-grid formed by the distributed ESS, the PV systems, and loads.

The Proposed method is based on the frequency bus-signaling of ESS and uses only local measurements for power distribution among micro-grid elements. Basic power management function is achieved locally at primary level, while strict frequency regulation can be achieved by using additional secondary controller.

Fig.1 shows a flexible micro-grid consists of RESs and ESS with batteries which can operate in either grid connected mode or islanded mode according to the state of

Intelligent Bypass Switch (IBS). In islanded operation, the ESS usually works as grid forming unit to maintain the common grid bus. Since islanded micro-grid has no power exchange with main grid, the ESS also has to operate as energy buffer to balance the power between sources and loads. Therefore, to obtain a reliable energy management function among RESs, ESS and loads, the capability of ESS based on SoC is very important.

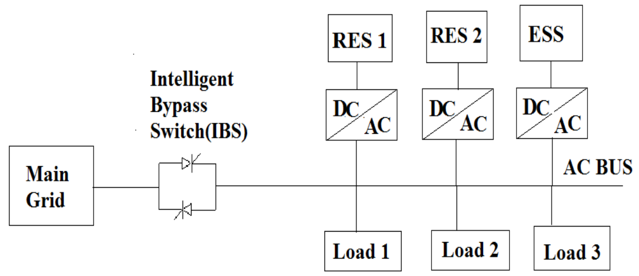

Fig -1: Micro-grid Configuration[s]

A. Primary Controls

The primary control in micro-grid is developed aiming at regulating the output power of each unit, at the same time maintaining the stability of bus voltage and frequency. Usually, the ESS and RESs units are controlled as master-slave way as Fig.2 presented. The ESS works as master unit maintaining AC bus voltage E* and frequency f*, and RESs operate as slave units regulating its output power according to MPPT.

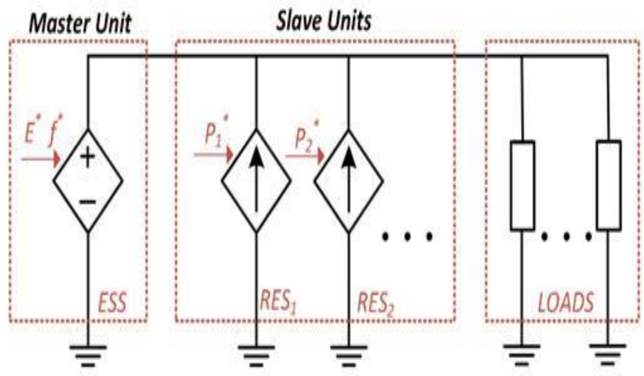

Fig -2: Master Slave Control of Islanded Micro-grid [11]

The coordinated control strategy can be classified into primary local level and secondary centralized level. In the primary level, there is no need of communication among ESS and RESs units. According to estimated SOC, the ESS changes the bus frequency as signaling, and RESs receive the signaling in AC bus to change the output power. However the frequency deviation will result in this level. Then if requirement for the tight frequency range is needed, additional secondary control level can be applied to restore frequency in nominal value with low bandwidth communication link.

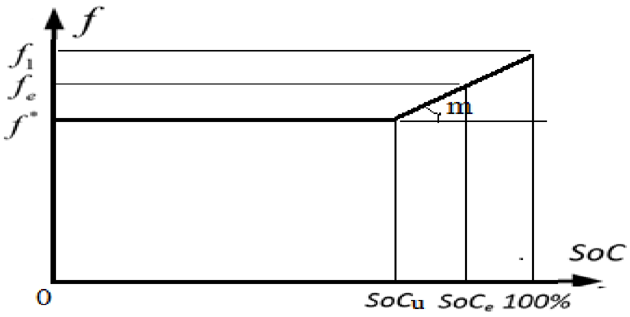

Fig -3: ESS Frequency Signals [11]

B. Master Control- ESS

When the output impedance of converter is highly inductive, the active power can be controlled almost exclusively by the output frequency. Therefore, it makes sense using frequency of ESS as signal to coordinate units when SOC approaching high. Fig.3 shows the diagram of ESS frequency signaling. f* and f_1 are the normal frequency and maximum frequency, and $SOCu$ is the SOC threshold of ESS. f_e And SOC_e are the final value of frequency and SOC. When SOC is lower than the up threshold, the ESS regulates its output frequency as nominal value. When SOC is higher than the threshold, the frequency then increases with slope of m to coordinate other units to maintain SOC. The output frequency of ESS is determined as

$$f = f^* \qquad SOC \le SOCu \qquad (1)$$

$$f = f^* + m(SOC - SOCu) \qquad SOC > SOCu$$

Where the boost frequency coefficient 'm' can be defined as,

$$m = \frac{f1 - f^*}{100\% - SOC_u} \qquad (2)$$

According to different SOC scenarios, the ESS bus-signaling control can be classified into high SoC control and low SOC control. The high SOC control targets the coordination between the ESS and PV system when micro-grid system continuously generates excess of renewable energy which leads to high SOC level. When SOC is critically high and goes beyond upper threshold SOCu, the ESS increase output frequency to order to inform the PV systems that they need to start decreasing power generation. In the high SOC range (SOCu, 100%), shown as the GFC block in Fig.4, the ESS regulates frequency with slope of m1 for bus-signaling. Similarly, when SOC is below low-threshold SO Cd, the ESS is tends to over-discharge situation. In this range (SOC0, SO Cd), the ESS controls bus frequency to constantly decrease from nominal value with slope m2 to induce the loads shedding procedure. When the SOC is in the safe range (SOCd, SOCu), bus frequency is kept at nominal value f*.

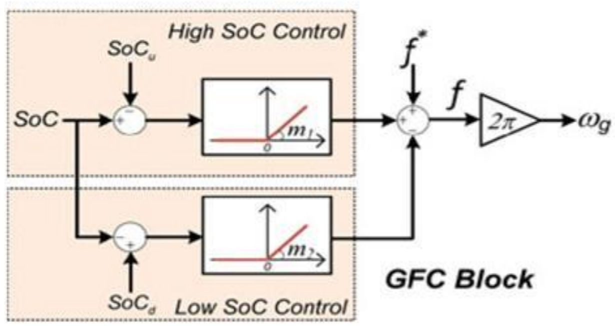

Fig -4: GFC Control algorithm of ESS[s]

C. Slave Control- RES

Having the frequency increasing, each RES unit decreases power from maximum power point. This performance is similar with the inertia response of the power system. In this case, the power drop of RESs may be achieved by adding virtual inertia of system. Fig.5 shows the virtual inertia performance of RESs, where Pref is the active power reference of RESs, PMPPT and p_e referred to the MPPT point and final power output of each RES, and f_{meas} is the sensing frequency by the phase lock loop (PLL). When f_{meas} not above nominal frequency, RES units are working under MPPT state, and making the full use of renewable energy. When f_{means} is above f*, RES units start to decrease output power to limit SOC of ESS. As the frequency reflects the SOC information, the higher is the bus frequency, the lower is the power from RESs. Finally, when the power absorbed by the ESS is low enough to maintain SoC, the frequency will be stable at fe, and power from RES unit has decreased to Pe. Thus the active power reference of each RES can be expressed as following

$$P\ ref = PMPPT \qquad fmeas \leq f* \qquad (3)$$

$$P\ ref = P\ MPPT - n\ (fmeas - f*) \qquad fmeas > f*$$

Where $n = \frac{P\ MPPT}{f1 - f*}$ (4)

Usually the micro-grid frequency is measured by the RES by means of PLL, which can be approximated as a first order system. Hence, the measured frequency f_{meas} can be expressed as

$$\text{fmeas} = \frac{f}{s\sigma+1} \qquad (5)$$

Here, σ is the time constant of the PLL.

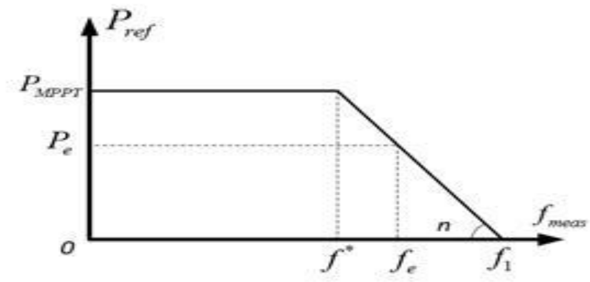

Fig -5: Series Virtual Inertia of RES [11]

Considering that the system is working in the condition SoCu<SoC<100%, and from (1) to (5), the RES power reference takes the form

$$P\ ref\ (s) = PMPPT + \frac{n\sigma}{\sigma s+1} f - n.m(SOC - SOCu) \qquad (6)$$

D. Secondary Coordinated Control

As previous analyzed, the bus signaling of ESS with only primary control results in frequency deviation. Although this frequency deviation can be designed inside the allowable limits, but some events like reconnection to main grid or synchronous machines connection to the micro-grid may require tight frequency regulation. When SOC >SOCu, the f – SoC curve of the ESS shifts downwards in order to regulate the micro-grid frequency in steady state. Then, we can modify the control strategy by adding a shifting-frequency term, thus

$$f = f* \qquad SOC \leq SOCu$$

$$f = f* + d\ f + m(SOC - SOCu) \quad SOC > SOCu$$

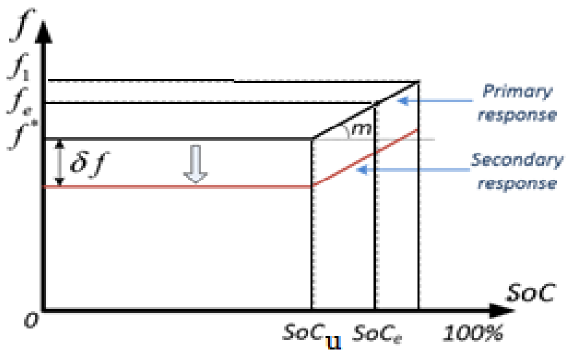

Fig -5: Combination of FBS of ESS and secondary control action [11]

On the other hand, if we restore the frequency in the micro-grid, then the effect of the RES primary control will be cancelled, so that we need to change the frequency threshold of equation (2), which can be modified as following:

$$Pref = PMPPT \qquad fmeas \leq f* + \delta F \quad (8)$$

$$Pref = PMPPT - n(fmeas - f* - \delta F) \quad fmeas > f* + \delta F$$

Now, the frequency threshold, instead of f* also incorporates the shifting frequency term δF.

E. Block Diagram of Proposed system

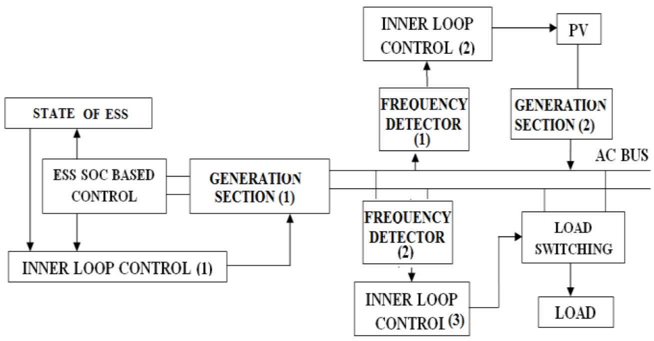

Fig -7: Block Diagram-Proposed interconnected system

ESS (SOC Based Control) + State Of ESS unit serves the power to bus lines. It will store the energy with pre-defined threshold. Typically lead acid battery is used. Overcharge and deep-discharge protection is incorporated in the battery sensing unit. SoC state generates output according to the inner state of the battery bank.

Inner Loop Control (1) is sub system block used as a feedback loop between ESS SOC state and generation section. Based upon ESS threshold level (high 95%,low 45%) this block generates a signal, frequency of which will be modified by generation section. This section will maintain ESS in proper condition. Generation Section (1) is having digitally controlled inverter. A PWM signal is fed to this section, which will change the generation frequency with pre-defined levels. A feedback is provided to inner circuit which will automatically bring up the output frequency to desire level depends on input PWM signal.

Frequency Detector is used on bus sensor point as bus line communication is carried out with frequency signaling method. Line frequency will be sensed and compared with pre-defined set values between threshold limits. This section will generate proportional output signal based on input sensed frequency. Inner Loop Control (2) section is connected between bus frequency sensor and PV generation part. When feedback signal will be arrived from frequency detector, this section will control amount of power generated by PV. This will help to avoid the use of dump load which affects the overall efficiency. Also, with smooth switching sudden spikes can be avoided in the bus.

Generation Section (2) is Similar to generation section (1). It generates output power which is linked to ESS and load. Based on SOC, the overall output of PV is combined with this section and optimized. In practice, this section considers to be a line connected inverter to maintain the overall power to the bus. Inner Loop Control (3) receives inputs from frequency detector which is continuously monitoring bus frequency. It is equipped with a demand control which will decide the switching state of the load. Load Switching Section is a final load control section which will connect or disconnect the supply fed to the load according to the priorities.

4. EXPECTED RESULTS

As an implementation part of the system, by assuming some of the given conditions we can expect the output of the system with following proposed results;

1. According to the ESS state, primary control block should change the bus signal frequency in predefined levels.
2. With the change in bus signal frequency, second block should adjust the power generation from PV generation system to match the requirement of ESS section.
3. At the same time, as load switching is also included in the system, third block should make the proper priority load switching based on bus frequency.

In common to all three sections, primary aim of bus signaling system should be implemented with local control based algorithm loop. Any advance microcontroller (AVR/CORTEX) based platform can be used to demonstrate different modes of the system.

On demonstration level, minimum 100W capacity model can be used with PV generation ratings near to 1/10 of total throughput of the system.

5. CONCLUSIONS

This study proposed self-governing autonomous active power control based on frequency bus signaling method to coordinate distributed components of is-landed micro-grid consisting of the ESS, the PV systems, and loads. By the proposed method, SoC of the ESS can be maintained within the safe limits by automatic adjustment in the power generation from the PV systems and load consumption. The electrical frequency of the micro-grid is used to inform the power sources to generate the power in order to maintain the ESS state of charge below or equal its maximum allowable limit. This coordination performance is obtained by using only local controllers and does not rely on external communication links. Therefore, the risk induced by the failure of the communication links can be avoided and thereby the reliability of the system is enhanced. Also, a centralized secondary control can be applied to effectively eliminate deviation of the bus frequency. Finally, the proposed control strategy is verified by the simulation results.

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