Centralized Controller for Microgrid

Adel Hamad Rafa

Abstract—This paper, proposes a control system for use with microgrid consist of multiple small scale embedded generation networks (SSEG networks) connected to the 33kV distribution network. The proposed controller controls power flow in the grid-connected mode of operation, enables voltage and frequency control when the SSEG networks are islanded, and resynchronizes the SSEG networks with the utility before reconnecting them. The performance of the proposed controller has been tested in simulations using PSCAD.

Keywords—Microgrid, Small scale embedded generation, island mode, resynchronization.

I. INTRODUCTION

THE capacity of small scale embedded generation (SSEG) connected to distribution networks in the United Kingdom (UK) is currently very small as many technologies are still at an early stage of their development or commercialization. However, this is set to increase with the backing of supportive governmental policies expected over the coming decade. A number of scenarios have recently been created by academic consortia, government agencies and trade associations to give an estimate for future capacity by considering the range of externalities that may impact on the electricity supply industry in the UK examples include in [1]-[3]. As an illustration, the four scenarios developed jointly by the EPSRC Supergen III consortia [1] provide a projection of 6GW of SSEG by 2020 within their 'Environmental Awakening' scenario. Given the support for these technologies within the 2007 UK government energy white paper [4] and the wider scenario-based projections, the issue of SSEG is expected to be of growing interest within the industry as generation technologies mature and become more affordable.

Small scale embedded generation networks (SSEG networks) are designed to be isolated from the distribution system during disturbances. They intentionally disconnect when the quality of power from the grid falls below certain standards [5], [6]. Once these problems are resolved they reconnect back to the grid. Normally, in grid-connected mode, the small sources act as constant power sources, which are controlled to inject the demanded power into the network. In islanded mode, small sources are controlled to supply all the power needed by the local loads while maintaining the voltage and frequency within acceptable operating limits [7]. Moreover, the existing power utility practice often does not allow islanded operation and automatic resynchronization of a SSEG network.

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However, the high penetration of SSEGs potentially necessitates provisions for both islanded and grid-connected modes of operation and smooth transfer between the grid-connected mode and the islanded mode to enable the best utilization of the SSEG network resources [8].

II. CONTROL APPROACH FOR A SYSTEM WITH MULTIPLE SSEG NETWORKS

A specific area with high levels of SSEGs, for example a city, could be divided into many areas, each of which is represented by one SSEG network. The interconnection of these individual SSEG networks forms multi-SSEG networks. This new concept is formed at the Medium Voltage (MV) level, consisting of LV SSEG networks connected on several adjacent MV feeders. SSEG networks under Demand Side Management control can be considered in this network as active cells, for control and management purposes [9]. These SSEG networks should be able to operate when they are in grid-connected or islanded modes, and should transition reliably through the connection/disconnection event [10]. Thus the technical operation of such a system requires the transposition of the SSEG network concept to the MV level, where all these active cells, as well as MV/LV passive substations, should be controlled by a Central Autonomous Management Controller (CAMC). This CAMC would be installed at the MV bus level of a HV/MV substation, serving as an interface to the Distribution Management System (DMS), and under the responsibility of the Distribution System Operator [11].

III. NETWORK USED IN THE STUDY

The basic power system model of the small rural network as shown in Fig. 1 [12], has been used to evaluate the performance of the general control approach that this work proposes. As shown the Central Management Controller (CMC) is located between five SSEG networks and the grid. The SSEG networks are connected to this network through the sub-sea cable at buses 1111 (0.55 MW), 1112 (0.04 MW), 1113 (0.77 MW), 1114 (2.7 MW) and 1115 (2.85 MW) all of which operate within the appropriate power factor range (0.95 lagging or leading). The load connected at these SSEG networks are 1111 (0.55MW, 0.11MVAr), 1112 (0.04MW, 0.01MVAr), 1113 (0.77MW, 0.15MVAr), 1114 (2.7 MW, 0.55MVAr) and 1115 (2.85 MW, 0.58MVAr). Every SSEG network has its own control system, named the SSEG network central controller (EGCC). The central energy storage device and the controller (CESC) are connected on bus 321.
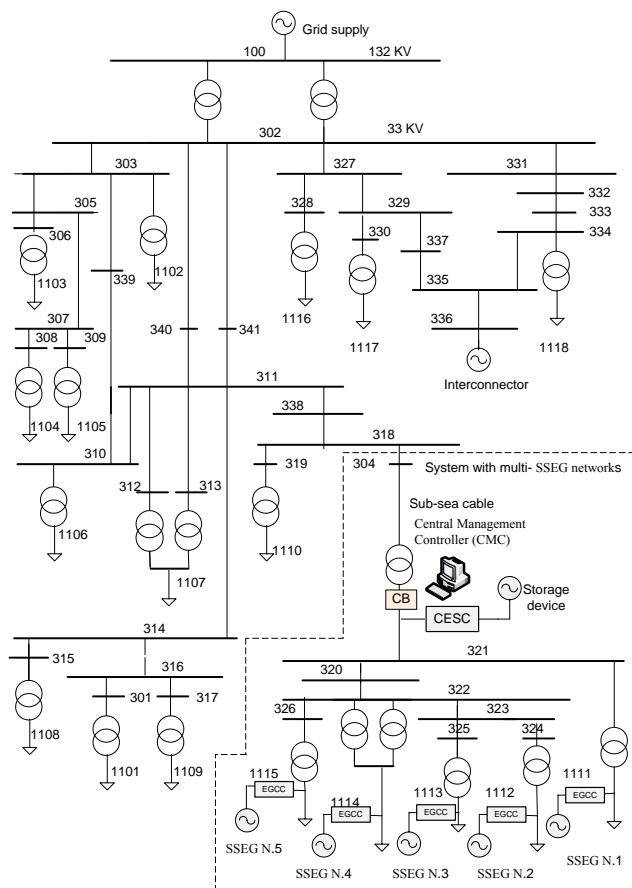
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Fig. 1 Network with multiple SSEG networks used in the analysis

IV. CONTROLLER DESIGN

In order to regulate the power flow of SSEG networks in the grid–connected mode and islanded mode, the SSEG networks should have a certain amount of control. This control system must fulfill a number of tasks. For this purpose several control elements are used. The objective of the control design for multiple SSEG networks is to offer a solution for power control along with voltage regulation in islanded as well as grid-connected modes.

A. Control Goals

This control system must fulfill a number of tasks:
- It needs to facilitate new SSEG connection to the system without disturbing the controller's operation.
- Keep the SSEG networks bus voltages within specified limits during grid-connected mode.
- Control active power and reactive power.
- Detect loss-of- mains conditions.
- Connect to or isolate the SSEG networks from the main network in a rapid and seamless fashion.
- Maintain both voltage and frequency within the standard permissible levels during islanded operation of the SSEG networks.
- Synchronise the SSEG networks to the grid after islanding.

B. Control Elements

Three control elements are distinguished, as presented in Fig. 2
- Central Management Controller (CMC).
- Central Energy Storage Devices Controller (CESC).
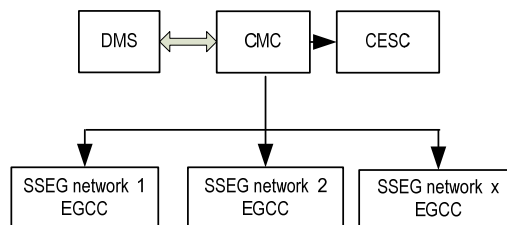- SSEG network Central Controller (EGCC).

Fig. 2 Control elements

1) Central Management Controller (CMC)

The Central Management Controller (CMC) is installed at the MV bus on the 33kV sub-sea cable between the SSEG networks and the main grid, serving as an interface to the Distribution Management System (DMS), and under the responsibility of the Distribution Network Operator (DNO). The block diagram of the CMC and the direction of the output signals can be seen in Fig. 3. The CMC contains loss-of-mains detection controller (LOMDC) and synchronizing controller (SC). The function of the LOMDC is to detect the loss-of-mains and isolate the SSEG networks from the system by sending a signal to the circuit breaker when the main generation is lost. However, the function of the SC is to compensate for the difference in magnitude and angle of the SSEG networks and grid voltages and to verify the synchronization conditions. Once the conditions are satisfied it sends a signal to the circuit breaker to reconnect the SSEG networks.
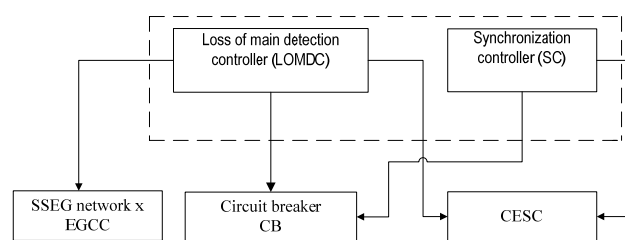

Fig. 3 Block diagram of CMC and the direction of the output signals

i. Loss-of-Main Detection Controller (LOMDC)

To effectively integrate SSEG networks into distribution networks, several requirements, such as voltage regulation, loss-of-mains protection and the sustainability of SSEG networks following disturbances on the associated network need to be satisfied [13]-[15]. The loss-of-mains protection may consist of one of the following protections: reverse power flow, neutral voltage displacement, directional over-current, rate-of-change of frequency (ROCOF) and change of power factor. In this work an islanding detection algorithm was

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developed to be responsible for switching between the grid and islanded modes of operation. This is operated by sending signals to open the circuit breaker between the SSEG networks and the main grid and change the control mode of CESC.

In this work a loss-of-mains protection scheme depending on the ROCOF, has been implemented. As shown in Fig. 4 the relay block diagram consists of a derivative component, which determines the rate at which the frequency of the system is changing (df/dt). The output value of the derivative (ROCOF) is compared with a preset threshold value (0.125 Hz/s) [16]. During the initialization the relay is deactivated**.** If the ROCOF exceeds the threshold value this means the main generation is lost and the output will be logic true (1), otherwise the output is logic false (0). This output will be the input of the OR logic gate, its output value is logic false (0), during steady state the output remains logic false (0). If the disturbance is detected the input of the OR gate becomes 1 and the output changes to logic true (1). This signal goes to the circuit breaker to open the circuit. Using the selector switch the circuit breaker B1 can be kept closed or controlled by the loss-of-mains protection scheme and synchronizing relay. When a utility fault occurs, the main circuit breaker on the 33kV bus opens to isolate the SSEG and utility networks within one frequency cycle. At the same time it sends a signal to the central storage device to switch from PQ control to voltage and frequency control (VF).
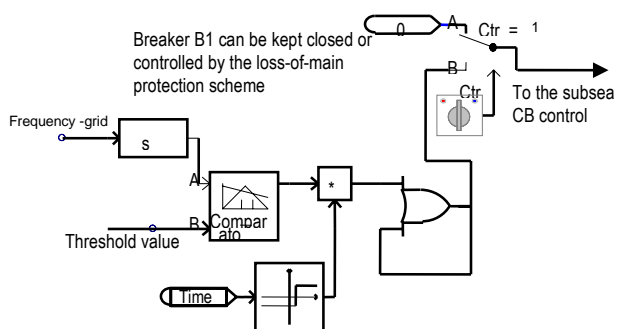

Fig. 4 Loss of main relay block diagram

ii. Synchronization Controller (SC)

In order to reconnect the SSEG networks to the main grid it is necessary to synchronize the SSEG networks to the grid at the point of connection. Hence the following conditions must be fulfilled.

▪ The SSEG networks voltage must be the same as that of the main grid.
▪ The frequency of the SSEG network must be the same as that of the main grid.
▪ The SSEG networks voltage must be in phase with the main grid.

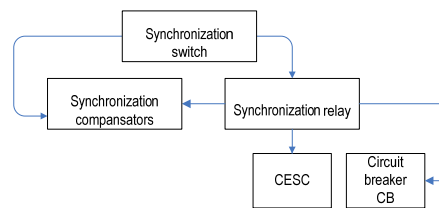Fig. 5 shows the block diagram of the synchronisation controller (SC).

Fig. 5 Synchronization controller (SC)

a) Synchronizing Procedure

When the utility grid returns back to normal operating conditions, the SSEG networks have to be resynchronized with the utility grid before the circuit breaker can be reclosed to smoothly return the system back to the grid-connected mode of operation. Synchronization can be achieved by aligning the phase angle and magnitude of the three-phase voltages at the SSEG networks and utility ends of the circuit breaker shown in Fig. 1. To align these voltages phase angles and magnitudes, two separate synchronization compensators are added to the external voltage and frequency control loops of the central energy storage device. As shown in Fig. 6 and 7, the inputs to these synchronization compensators are the magnitude and phase errors of the two voltage phasors at both ends of the circuit breaker. Their outputs are fed to the real and reactive power loops to make the voltage phasor at the SSEG networks end track the phasor at the main grid end closely (both in magnitude and frequency). Also during resynchronization, the voltage and frequency references of the central energy storage device are changed to achieve the same voltage magnitude and frequency at the connection point as that of the grid voltage while the SSEG networks maintain the supply to the demand. When synchronization criteria are acceptable the circuit breaker will be closed, thus the SSEG networks are reconnected to the main grid. Once the SSEG networks are reconnected, the synchronization compensators must be deactivated by setting their outputs to zero so as not to interfere with the proper operation of the real and reactive power control loops in the grid-connected mode.
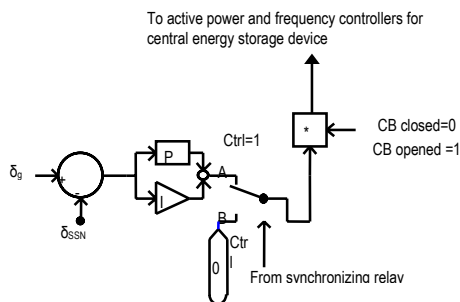

Fig. 6 Voltage angle synchronizing compensator

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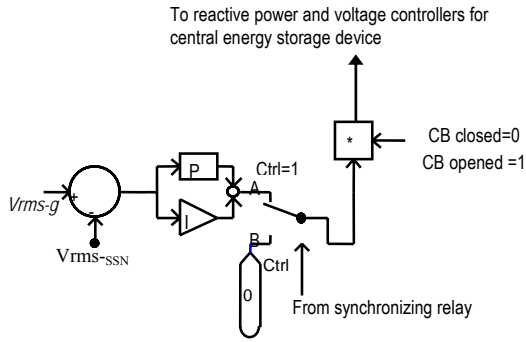Vol:7, No:9, 2013

Fig. 7 Voltage magnitude synchronizing compensator

The transfer function of the voltage angle synchronizing compensator is given by the equation below:

$$P_{com}(s) = K_{pc\delta}\left[1 + \frac{1}{\tau_{ic\delta}S}\right].E_{\delta}(s) \qquad (1)$$

where

$$E_{\delta}(s) = \left[\delta_g(s) - \delta_{SSN}(s)\right] \qquad (2)$$

$K_{pc\delta}$: proportional gain of voltage angle synchronizing compensator PI controller,

$\tau_{ic\delta}$: integral time constant of PI controller ($\tau_{ic\delta} = \dfrac{K_{pcop}}{K_{icop}}$ where $K_{ic\delta}$ is the integral gain).

Similarly the transfer function of the RMS voltage magnitude synchronising compensator is given by the equation below:

$$Q_{com}(s) = K_{pcv}\left[1 + \frac{1}{\tau_{icv}S}\right].E_V(s) \qquad (3)$$

where

$$E_V(s) = \left[Vrms_g(s) - Vrms_{SSN}(s)\right] \qquad (4)$$

K_{pcv}: proportional gain of RMS value of the voltage magnitude synchronizing compensator PI controller,

τ_{icv}: integral time constant of PI controller ($\tau_{icv} = \dfrac{K_{pcv}}{K_{icv}}$ where K_{icv} is the integral gain).

b) Synchronization Relay

This controller performs a check synchronization function which compares the voltage (angle and magnitude) on either side of the CB at the point of connection (SSEG networks and grid voltages) before issuing a reclose command. In addition it activates the synchronization compensators to correct for the difference between the SSEG networks and the grid voltages (magnitude and angle) before reconnecting the SSEG networks to the main grid. Fig. 8 shows schematic diagram of the synchronization relay block diagram.

The first selector switch and two-state switch (ON, OFF) form the synchronization switch. The output of the selector

switch component will be either the signal connected to A, or the signal connected to B, depending on the value of Ctrl. The Ctrl is changed by the two state switch (ON, OFF), if the switch is ON the Ctrl=1 then the output will be the signal connected to A which is logic true (1). This signal will be one of the inputs to the logic gate AND, and also goes to the synchronization compensators to activate them. On other hand if Ctrl=0 then the output will be the signal connected to B which is logic false (0). This synchronization switch is switched ON by the distribution network operator (DNO) to start the synchronization procedure (ON=1, OFF=0).
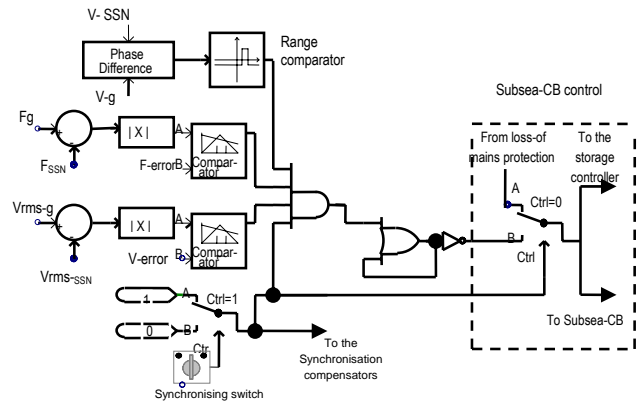

Fig. 8 Synchronizations relay

The voltage waveforms of the SSEG networks and the grid are the inputs of the phase difference component as shown in the upper part of Fig. 8. The phase difference component determines the phase angle difference (Ph_{error}) between the voltages of the SSEG networks and the grid. The phase angle difference is positive if the SSEG networks side's voltage leads the grid voltage otherwise it is negative. The phase angle difference (Ph_{error}) is the input to the range comparator. The range comparator determines which of three ranges the input signal belongs to, and then outputs a value corresponding to that region. The regions are defined by a lower input limit $Ph_{error}<0$ and an upper input limit $Ph_{error}>0$. The first region is composed of values below the lower limit (the SSEG networks side's voltage lags the grid voltage); the second region is Ph_{error} = zero which is between the two limits (normal operation); and the third region is composed of values above the upper limit (the SSEG networks side's voltage leads the grid voltage). The output of the range comparator is logic true (1) for Ph_{error} = 0 and logic false (0) for $Ph_{error}<0$ or $Ph_{error} > 0$.

The first difference junction subtracts the filtered measured frequency of the SSEG networks from the filtered measured frequency of the grid, the difference will be the frequency error f_{error} which is given by the equation below:

$$f_{error} = f_g - f_{SSN} \quad [Hz] \qquad (5)$$

f_g is the measured grid frequency [Hz], f_{SSN} is the

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measured SSEG networks frequency [Hz].

The upper two input comparator component will output logic true (1) if the frequency error $|f_{error}| \geq 0.002$ otherwise the output is logic false (0).

The second difference junction subtracts the RMS value of the measured voltage of the SSEG networks side from the RMS value of the measured voltage of the grid. The difference will be the voltage V_{error} which is given by (6).

$$V_{error} = V_{rms\,g} - V_{rms\,SSN} \quad [kV] \qquad (6)$$

where: Vg is RMS measured grid voltage [kV] and, Vsn is the RMS measured SSEG networks voltage [kV].

The output of the lower two input comparator component will be logic true (1) if the voltage error $|V_{error}| \geq 0.01$ otherwise the output is logic false (0).

The output of the AND gate is logic true (1) if all synchronization conditions are satisfied, otherwise the output is logic false (0). The OR gate holds the output constant (logic false (0)) until the input signal is changed to logic true (1), then the new output will be logic true (1). The function of the inverter is to invert the output of the relay, because the signal (0) here means close the circuit breaker. The function of the second selector is to change the source of the command signals that go to the subsea cable circuit breaker and the central energy storage device. If the synchronization switch is ON the output signal will be the signal from the synchronization relay, otherwise the output will be from the loss-of-mains protection or from the control panel by the distribution network operator (DNO).

2) Central Energy Storage Device Controller (CESC)

The control schemes of the storage device are PQ control or Frequency/Voltage control. The storage device provides voltage and frequency control of the SSEG networks when the SSEG networks are operated in islanded mode. During the grid-connected mode the control technique of the energy storage device is PQ control. When the main circuit breaker opens to isolate the SSEG networks from the utility grid, the system must immediately keep the balance between load and generation using the storage devices or by the load-shedding technique to continue supplying power to all critical loads within the SSEG networks adequately. In this case the storage device controller receives a signal from the main controller to switch from PQ control mode to voltage and frequency control modes.

   i. PQ Control for Central Storage Device

The control of the active power is realized by controlling the load angle δ_{st} and reactive power is controlled by controlling the voltage magnitude V.

a) Active Power Controller for Central Storage Device

As shown in Fig. 9, during grid–connected mode the central controller sends a signal to deactivate the two PI controllers. Thus only the first PI is activated, which would suffice to

control the flow of active power by generating the proper values for δ_{st} as described in the following equations:

$$\delta_{st}(s) = K_{pstp}\left[1 + \frac{1}{\tau_{ist\delta}S}\right].E_P(s) \qquad (7)$$

where

$$E_P(s) = \left[P_{st-ref}(s) - P_{st-meas}(s)\right] \qquad (8)$$

K_{pstp} : proportional gain of storage device PI controller,

τ_{istp} : integral time constant of PI controller ($\tau_{istp} = \frac{K_{pstp}}{K_{istp}}$

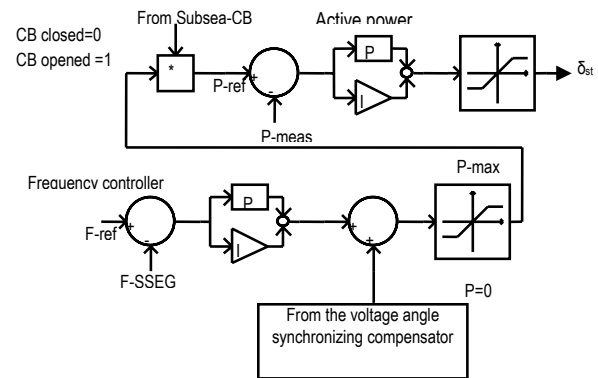where $K_{ist\,p}$ is the integral gain.

Fig. 9 Active power and frequency controllers for central energy storage device

In this study during the grid–connected mode, the output active power of the storage device is kept zero. In islanded mode the active power reference value is received from the frequency controller. This will be discussed later in this paper.

b) Reactive Power Controller for Central Storage Device

The first PI controller in Fig. 10 controls the reactive power injected or absorbed by the central storage device. During the grid-connected mode the controller maintains the output reactive power of the storage device at zero level. However during islanded mode the controller controls the flow of the reactive power according to the reference reactive power value issued by the voltage controller. Controlling the reactive power is performed by generating the proper values for V_{st}, as described in the following equations:

$$V_{st}(s) = K_{PV}\left[1 + \frac{1}{\tau_{iV}S}\right].E_Q(s) \qquad (9)$$

where

$$E_{Q-st}(s) = \left[Q_{st-ref}(s) - Q_{st-meas}(s)\right] \qquad (10)$$

K_{pV} : Proportional gain of PI controller.

τ_{iV} : Integral time constant of PI controller ($\tau_{iv} = \frac{K_{pV}}{K_{iV}}$ where K_{iV} is the integral gain).

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$Q_{st-meas}$: Storage device measured reactive power.
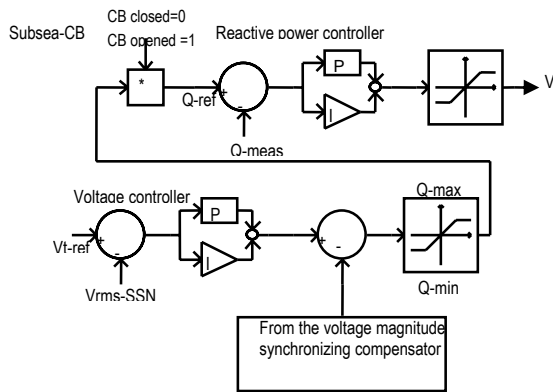

Fig. 10 Reactive power and voltage controllers for the central energy storage device

ii.   Frequency /Voltage Control using Central Storage Device

Control of the frequency is realized by controlling the active power P, the control of the voltage is enabled by controlling the reactive power Q. At the instant of detection of the islanded operation by loss-of-mains protection, the central controller sends three signals at the same time, one signal to open the circuit breaker and the other two signals to change the operation of the storage device from PQ control mode to frequency and voltage control mode.

a) Frequency Controller

The objective of the frequency controller is to restore the frequency to its normal value. This is accomplished by increasing or decreasing the required active power from the storage device to maintain the system frequency at a constant value. The implementation of frequency control is shown in Fig. 9. When islanded operation is detected by the loss-of-mains protection, the controller receives a signal from the central controller to activate the frequency controller (second PI controller). The PI controller compares the system frequency with a reference value (50 Hz) and restores the frequency of the SSEG networks near the set value, by generating the proper value of active power. This value of active power becomes the input reference value of the active power controller. The frequency controller is described in the following equations:

$$P_{ref}(s) = K_{pf}\left[1 + \frac{1}{\tau_{iA}S}\right].E_f(s) \qquad (11)$$

where

$$E_f(s) = \lfloor f_{ref}(s) - f_{meas}(s)\rfloor \qquad (12)$$

where f_{ref} and f_{meas} are reference frequency and the measured SSEG networks frequency respectively. K_{pf} is the proportional gain of the PI controller, τ_{if} is integral time

constant of the PI controller that equals $\frac{K_{pf}}{K_{if}}$ where K_{if} is the integral gain.

b) Voltage Controller

The implementation of the voltage control is shown in Fig. 10. When islanded operation is detected by the loss-of-mains protection, the controller receives a signal from the central controller to activate the voltage controller (the second PI controller). The second PI controller compares the bus voltage at the point of connection with a reference value (e.g. 1.0 p.u) and restores the voltage at this point near the set value by generating the proper value of reactive power (inject or absorb). This value of reactive power becomes the input reference value of the Q controller of the storage device. The voltage controller of the storage device is described in the following equations:

$$Q_{ref}(s) = K_{pv}\left[1 + \frac{1}{\tau_{iv}S}\right].E_V(s) \qquad (13)$$

where

$$E_V(s) = \lfloor V_{ref}(s) - V_{meas}(s)\rfloor \qquad (14)$$

where V_{ref} and V_{meas} are reference voltage and the RMS SSEG networks terminal voltage respectively. K_{pv} is the proportional gain of the PI controller, τ_{iv} is the integral time constant of the PI controller that equals $\frac{K_{pv}}{K_{iv}}$ where K_{iv} is the integral gain.

3) SSEG Network Central Controller (EGCC)

The main interface between the central controller of the whole SSEG networks and each individual SSEG network is the SSEG network Central Controller (EGCC). The EGCC is the main component responsible for the optimization of the SSEG network operation. Also the output power set points of the SSEGs are determined by the EGCC or by the owners. The problem is approached in this way because the assumption in this work is that each LV SSEG network is considered as a single bus with an equivalent generator (sum of all SSEGs) and an equivalent load (sum of all LV loads) connected to an 11kV bus. Thus the SSEG controller concept will transpose to EGCC.

i.   Active Power Control for SSEG Networks

Every SSEG network produces constant output active power during grid-connected and islanded modes. During grid-connected mode if the load increases in the system the extra power comes from the main grid. When the SSEG networks are islanded, the energy storage device compensates this difference between generation and demand. If energy storage is unable to match this demand then load shedding is implemented.

The active power controller is used to control the active power output from the SSEG networks, based on pre-specified

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set points (P_{ref}). The (P_{ref}) value can be set by the central controller or locally calculated according to a pre-specified power profile to optimize active power export from the SSEG network.

ii. Voltage Control for SSEG Networks

To maintain the voltage between acceptable limits, the SSEG network will adjust the reactive power in the network: it will inject reactive power if the voltage falls below the nominal value (for example the nominal value, 11kV) and will absorb reactive power if the voltage rises above its nominal value.

V. THE ALGORITHM OF THE CONTROLLER

The following steps are to summarize the operational principle of the proposed control system.

A. Control of SSEG Networks in the Grid Connected Mode

In grid-connected mode, the SSEG networks supply pre-specified power to minimize power import from the grid, and each SSEG is controlled to represent a PV-bus. The central storage device is controlled to represent a PQ-bus. Thus, the main grid is expected to accommodate the difference in real/reactive power supply and demand within the SSEG networks. In this mode, the voltage and frequency are established by the grid.

B. Control of SSEG Networks to Transition from Grid-Connected to Islanding Mode of Operation

When an abnormal condition occurs in the main grid and the main generation is lost. The tasks of the control system are:

- The loss-of-mains protection has to detect this event and send a signal to the circuit breaker between the SSEG networks and the main grid to disconnect the SSEG networks from the main grid [the SSEG networks are in islanded mode]. According to this condition df/dt≤ -0.125 Hz/s.
- The control of the energy storage device shifts to islanded mode of operation (voltage and frequency control).
- In this mode, the central energy storage device forms the grid by establishing its voltage and frequency; otherwise, the SSEG networks will collapse. Both voltage and frequency should be regulated within acceptable limits. If the frequency has dropped to excessively low levels, loads may be shed to hasten its recovery towards the nominal value.
- Balance between supply and demand, if the SSEG networks are exporting or importing power to the grid before disconnection, then the control system takes actions to balance generation and consumption in island mode.
- The SSEG networks control strategy is same as during grid connected mode (active power /voltage regulation through voltage-phase angle droop strategies).

C. Control of SSEG Networks to Transition from Islanding to Grid-Connected Mode of Operation

Finally, once service has been restored to the utility grid after an event has caused separation of the SSEG networks from the utility grid, the SSEG networks must be reconnected to the grid. In this case the controller matches the voltage sine wave of the SSEG networks with the voltage sine wave of the main grid at the point of connection and issues the command to close the breaker tying them together.

Sequence of actions during reconnection of SSEG networks:

- When the MV network becomes available, check if the voltage and frequency are within acceptable limits, if yes close the synchronizing switch (it is done automatically or by DNO) and go to the grid-connected mode.
- Activate synchronization compensators
- Synchronization conditions (phase sequence, frequency and voltage differences) should be verified to avoid large transient currents during reconnection.
- If the synchronization conditions are satisfied go to step 5 to close the circuit breaker otherwise wait until the conditions are satisfied.
- Send signal to close the circuit breaker to reconnect the SSEG networks
- Deactivate synchronization compensators
- Go to the grid-connected mode

VI. SIMULATION RESULTS

The performance of the proposed controller of the multiple SSEG networks connected to a 33 kV distribution power network through a subsea cable has been tested using PSCAD. This section introduces the results which display the operation of the controller under various operating conditions. The main quantities will be presented and an analysis of the results will be made.

A. Performance of SSEG Networks in Grid-Connected Mode

The test verifies the active power and voltage regulation control strategies of the SSEG networks when the system operates in grid-connected mode. First assume that the SSEG networks operate in grid-connected mode in steady state operation when there are no faults in the network (time 0-10 sec). Figs. 12-14 illustrate the performance of the overall system control, SSEG networks and central storage devices controllers. Each SSEG network central controller (EGCC) regulates the bus voltage of the SSEG network within standard limits and maintains constant real power output from each SSEG. Fig. 11 (a) shows that during grid-connected mode the SSEG networks import power from the main grid to accommodate the difference in real power demand within the SSEG networks. Also as shown in Fig. 12, during grid-connected mode there is no participation from the storage device in the active and reactive power flow of the system. At the same time, Fig. 11 (b) shows that the SSEG networks

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inject reactive power to the system providing voltage support. Also Figs. 13 (a)-(e) show that the terminal voltage of every SSEG network bus is regulated by the SSEG network itself due to the phase angel/voltage droop control. Fig. 13 (f) shows the voltage of the SSEG networks and the grid at the two ends of the PCC circuit breaker, which are sinusoidal waveforms and synchronized.
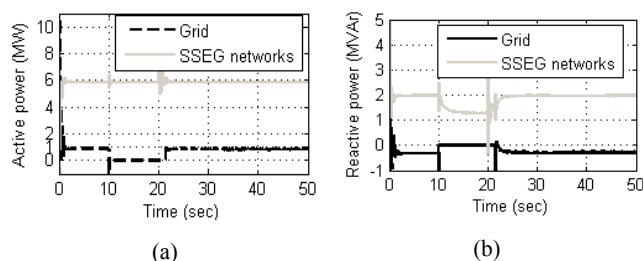

(a)   (b)

Fig. 11 Power exchange between SSEG networks and the grid: (a) active power and (b) reactive power
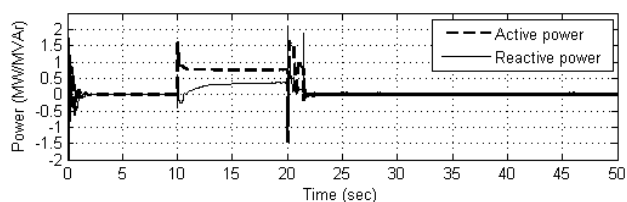
Fig. 12 Output of the storage device

(a)   (b)

(c)   (d)

(e)   (f)
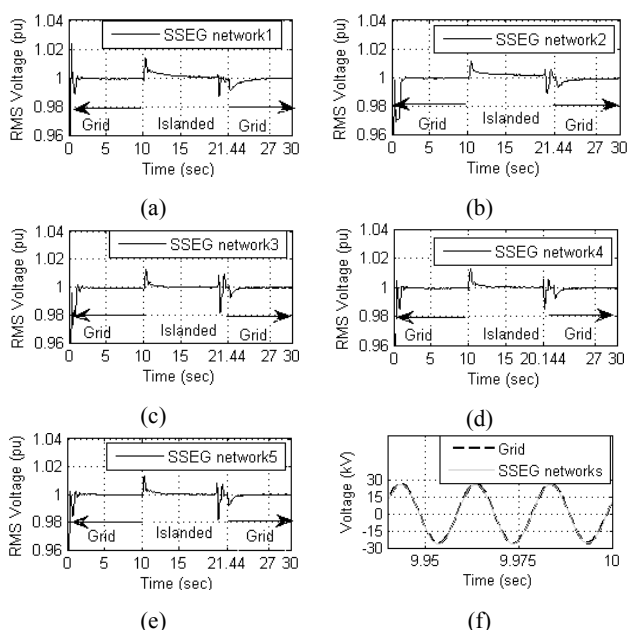
Fig. 13 (a), (b), (c),(d) and (e) RMS per unit of three phase terminal voltage of SSEG networks (f) Grid and SSEG networks voltages waveform (kV) during grid mode phase a

B. Performance of the SSEG Networks during Transition from Grid-Connected to Islanded Mode

The test verifies the frequency and voltage control strategies of the SSEG networks when the system operates in

islanded mode. A set of simulation scenarios were performed in order to evaluate the dynamic behavior of the SSEG networks during islanded mode. The evaluation includes disconnection from the upstream MV network (33kV) and load-following in islanded operation. Several scenarios were simulated. At the occurrence of a fault, the protection equipment disconnects the SSEG networks as a protective measure. In this case the assumption is that the fault in the main grid caused a loss-of-mains condition. This event was detected by the loss-of-mains protection algorithm which is part of the control system of the SSEG networks. Under this condition as shown in Fig. 14 the loss-of-mains protection sends a signal to the circuit breaker in the subsea cable between the SSEG networks and the grid to open the circuit as well as a signal to the central storage device controller to change the operation mode from grid-connected mode to islanded mode (from PQ control to V/F control). The operation of the SSEG networks seamlessly shifts from grid connected to island mode. The following figures show simulation results when the SSEG networks were operated in islanded mode (time 10-20sec). Fig. 11 (time 10-20sec) shows the constant active power output and the change in reactive power output (for local voltage control) of the SSEG networks when they transit from grid-connected to islanded mode. Fig. 12 (time 10-20sec) shows simulation results with the voltage and frequency regulation control technique operating in response to an abrupt change in load when the SSEG networks were operated in islanded mode. The storage device injects active and reactive power to maintain the terminal voltage and the SSEG networks frequency within acceptable limits. Furthermore, the waveforms showing the load terminal voltage and the circuit breaker currents during transfer from grid-connection to islanded mode are illustrated in Fig. 15. It is observed that no current passes through the circuit breaker between the SSEG networks and the main grid. However, the controller regulates voltage in all three phases and makes the transfer from grid-connection to island mode a seamless one.

C. Performance of the SSEG Networks during Transition from Islanded to Grid-Connected Mode of Operation

This test was held to investigate the synchronization processes between the grid and the SSEG networks. At the start of the test the SSEG networks were disconnected from the main grid (islanded mode). The regulating process during which the voltage of SSEG networks is synchronized with the utility grid's voltage is observed in the following figures. Before transfer from islanded mode to grid-connection, the grid voltage is inspected and verified to be within the acceptable limits as shown in Fig. 16. Then, the controller allows the SSEG networks voltage to synchronize with the grid voltage at the ends of circuit breaker (refer to Fig. 18), the synchronizing switch starts the synchronizing procedure and sends a signal to activate the two synchronization compensators at 20sec. The synchronization is done by means of aligning the three-phase space vectors of the two voltages. The synchronization relay checks whether the voltages on

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both ends of the circuit breaker are locked in magnitude and phase angle before making the decision to send a signal to close the Fig. 19 shows how the RMS values of the SSEG networks and grid voltages are synchronized before the circuit breaker is closed. Fig. 20 shows the frequency synchronization, the different frequencies are observed during the islanded mode. After the alignment of the voltages, the frequencies are synchronized. It can be seen in Fig. 22 that at the start of the test the phase angle values of the voltages of the main grid and the SSEG networks were different. However before the circuit breaker is closed as clearly seen in the results the phase shift and rms voltage values of the grid voltage match the SSEG networks voltage before the circuit breaker is closed. After 21.44sec the network was connected to the SSEG network.

The waveforms showing the synchronization to the grid and transfer from islanded mode to grid-connection at both ends of the circuit breaker when the synchronization algorithms start functioning in the islanded mode are illustrated in Fig. 19. It was observed that there is a difference in voltage magnitudes and angles of the SSEG networks system and the grid network during islanded mode. It can be seen that the proposed controller successfully forces the voltage at the SSEG networks end to track that of the main grid end without any power oscillation between the SSEG networks. In the first 300ms the difference in phase and magnitude between the SSEG networks and grid voltages is gradually decreasing, until synchronization conditions are fulfilled (at about 21.44 s as shown in Fig.18 the controller closes the circuit breaker). Subsequently, the system operates at a single voltage and frequency.

Fig. 22 illustrates the corresponding real and reactive power outputs of the storage device during the process of reconnection of the SSEG networks between 20- 21.44 sec. This figure shows an increase in both real and reactive power outputs, which are expected due to the higher SSEG networks output voltages during synchronization.

(a)   (b)
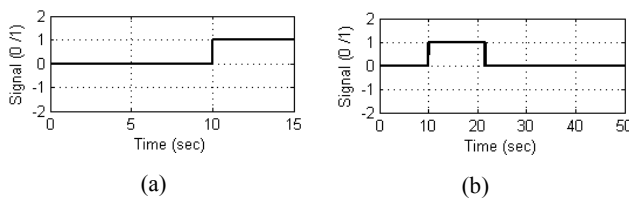
Fig. 14 (a) Control signals from LOMCD and (b) State of the circuit breaker

(a)   (b)
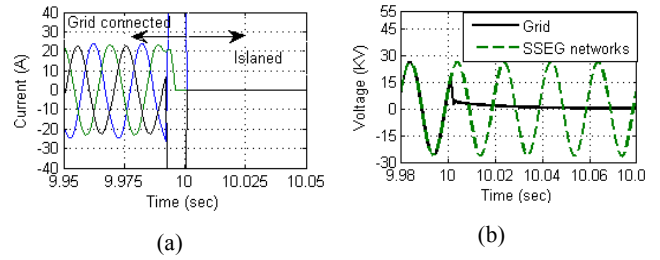
Fig. 15 (a) The circuit breaker currents and (b) The voltage at two ends of the circuit breaker during transfer from grid-connection to islanded mode (phase A)
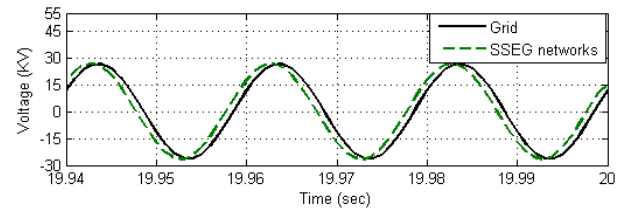
Fig. 16 Grid and SSEG networks voltages waveform (kV) during islanded mode
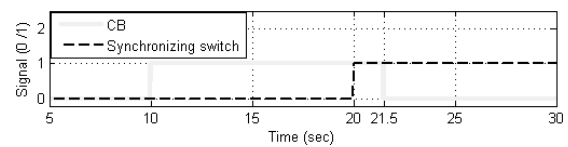
Fig. 17 Control signals for (CB and synchronizing switch)
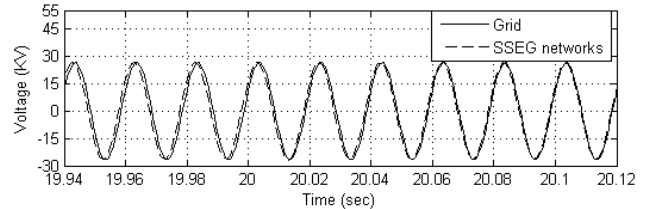
Fig. 18 Grid and SSEG networks voltages waveform (kV) during islanded mode and during synchronization
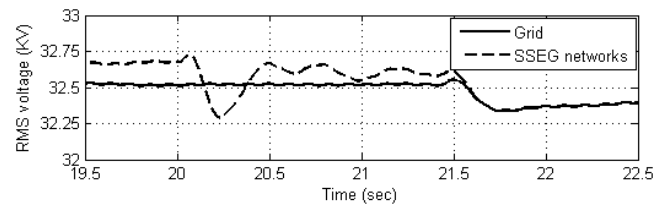
Fig. 19 RMS voltage of grid and SSEG networks at point of connection (Phase A)

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