A Novel BESS-based Fast Synchronization Method for Power Grids

Wang, G.; Sun, H.; Nikovski, D.N.; Zhang, J.

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Abstract

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Gang Wang
Dept. of Electrical and Computer Engineering
Tufts University, Medford, MA 02155,USA
Email: gang.wang@tufts.edu

Hongbo Sun, Daniel Nikovski, Jinyun Zhang
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139, USA
Email: {hongbosun, nikovski, jzhang}@merl.com

***Abstract*— This paper introduces a novel method for synchronizing two energized AC grids through a fast synchronization machine, which integrates a battery energy storage system (BESS) with a grid-imposed frequency voltage source power converter. The grid-imposed power converter is used to automatically provide the desired amount of power to the synchronous generators, and the BESS is connected to the DC side of the power converter, which exchanges energy with the grids. This method can achieve fast synchronization of grid frequencies and phases through active and automatic power exchanges between the battery based power converter and the grids. The effectiveness of the proposed method has been demonstrated by simulating interconnection of two synchronous generator based systems in the Matlab/Simulink environment. The simulation results show that compared with traditional methods the synchronization time can be reduced by an order of magnitude by using the proposed method.**

Index Terms--**Battery energy storage systems (BESS), fast synchronization machine, grid-imposed converter, in-rush current, synchronous generator.**

I. INTRODUCTION

With the growing installation of renewable generations, the power grid has much lesser inertia than before, and thus gives less time for the system to act for emergencies, such as sudden power imbalance. As an effective option for dealing with emergences, grid reconfiguration can help the system maintaining stable operation through reconfiguring the grid with switch operations [1]. However, the switch closing usually requires the voltage magnitudes, phase angles and frequencies between two terminals of switches are synchronized, therefore it takes a considerable time to make two energized grids synchronized using traditional synchronization methods. As pointed out in [2], the synchronization time can be as long as several minutes. Traditionally, the power system relies on the primary and secondary controllers of generators to achieve grid frequency and phase angle synchronization. Constrained by the dynamic characteristics of controllers (i.e. time constants), there is less room left for speeding up the synchronization process by improving the performances of primary and secondary controllers. Therefore, more effective methods are desired for achieving grid synchronization in a timely manner when a grid reconfiguration is required.

Battery energy storage system (BESS) has recently gained much attention, due to its capability of absorbing and delivering desired amount of powers through its charging and discharging processes. For example, [3] used BESS to realize frequency regulation through reducing frequency deviations resulting from sudden load variations. [4] explored using a BESS to perform several different tasks, including voltage regulation, load leveling, harmonic elimination and power factor improvement. Integrating with power converters, the BESS can also be utilized as a virtual synchronous machine (VSM) [5]-[7] to automatically deliver powers to the grid by encompassing frequency and voltage droop characteristics. The VSM can be used for reducing frequency and power oscillation in the grid [5], improving frequency response under severe frequency deviations [6], and mitigating grid instability in the presence of high penetration of distributed generations [7]. The BESS is integrated with a static synchronous compensator (STATCOM) in [8] to improve power grid stability. Inspired by those works, we have explored using battery energy storage systems (BESS) and power converters to realize the fast synchronization of power grids.

This paper proposes a fast synchronization machine used for interconnection of two energized grids, which integrates a BESS with a grid-imposed frequency voltage source converter. The grid-imposed power converter is used to automatically provide the desired amount of power to the synchronous generators, and the BESS is connected to the DC side of the power converter, which exchanges energy with the grids. Through absorbing or delivering desired amount of powers from or to the AC grid, the fast synchronization machine can realize the frequency and phase synchronization between two grids quickly. The structure of this paper is organized as follows. Section II gives a brief description for the traditional synchronization method. Section III describes in details the proposed fast synchronization machine and its operating mechanism. The general guidance of battery selection for the synchronization machine is also discussed in the section. Simulation results for two synchronous generator based systems are given in Section IV, which demonstrate the effectiveness of the proposed fast synchronization method. The conclusion is drawn at the end of this paper.

II. TRADITIONAL GRID SYNCHRONIZATION METHOD

For the synchronization between two grids, four criteria should be satisfied before closing the switch: grid frequency, phase difference, phase sequence, and voltage magnitude. In this paper, only the synchronization of grid frequency and phase difference will be considered since they are more difficult to achieve and have a superior impact on the system

*Gang Wang conducted this research during his internship at MERL.

performance.

Fig.1 displays the schematic of synchronization mechanism between two synchronous-generator based AC grids. The automatic generation control block is implemented with primary and secondary controllers, which reflects the dynamic responses of the governor and system frequency. With the help of an automatic generation controller, the frequency of the synchronous generator will approach the preset reference value in steady state. The auto-synchronizer will measure the frequency and phase difference between two systems, and close the switch if the synchronization requirement is satisfied.

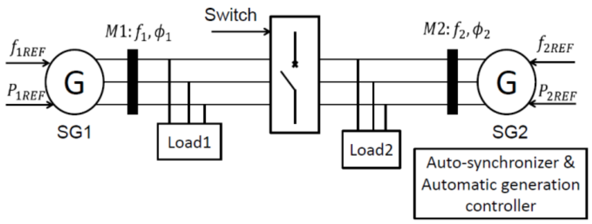


Fig.1. Schematic of traditional synchronization mechanism between two energized AC grids

Fig.2 gives the schematic of governor and turbine [9], where ΔY is the control signal of the valve/gate position, P_m is the mechanical power output of the turbine, P_e is the electrical power output of the generator, and $\Delta\omega_r$ is the rotor speed difference between the actual value and reference value.

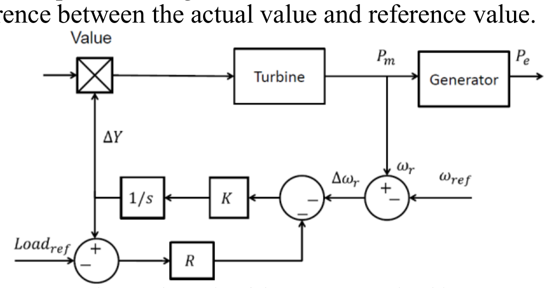


Fig.2. Schematic of the governor and turbine

This schematic includes the effects of droop-characteristic, turbine dynamics and generator dynamics. The droop characteristic is described as:

$$\Delta P = \Delta f / R \tag{1}$$

where R is determined as the ratio of speed deviation, $\Delta\omega_r$ or frequency deviation, Δf to the change in the valve/gate position, ΔY or power output, ΔP. This relationship indicates that the increase or decrease of electrical power on the load side can lead to corresponding amount of change in the system frequency at steady-state. Therefore, system frequency can be modified through changing the output electrical power. The generator dynamics can be expressed as:

$$J\, d\omega/dt = (P_m - P_e)/\omega_0 - D_e\omega \tag{2}$$

where D_e is the coefficient of friction loss of the synchronous generator. J is the moment of inertia, which stands for the ability to resist changes in the rotational speed. ω and ω_0 represents the angular and synchronous speed of the generator, respectively. Neglecting the effect of D_e, (2) can be simplified as

$$J\, d\omega/dt = (P_m - P_e)/\omega_0 \tag{3}$$

The dynamics of the generator can be utilized to actively adjust the speed of the synchronous generator. The fast synchronization machine is designed based on (3) and implemented with an automatic power compensation controller.

Using traditional synchronization methods, the synchronization process for the systems in Fig. 1 can be implemented through following steps:

Step 1: regulating the frequency reference of SG2, f_{2REF} to approach the normal operating frequency of SG1, f_{1REF}.

Step 2: performing frequency matching according to dynamic characteristics of primary and secondary controllers. In this step, the frequency of SG2 is gradually converging to its steady state. However, for the sake of phase synchronization, a small frequency deviation is remained between SG1 and SG2 at the end of this step.

Step 3: performing the phase matching. The auto-synchronizer monitors the phase difference between two systems and closes the switch if the phase deviation satisfies the required limit. The synchronization parameter limits are detailed in IEEE Standard 1547-2003 [10].

Step 4: After closing the switch, while aligning f_{2REF} with nominal frequency f_{1REF}, monitoring the frequency transient response and in-rush current within two systems.

Fig.3 gives the frequency responses of generators in Fig. 1 during a traditional synchronization process. As shown in Fig.3, using traditional method, the switch can be closed around 70s, and the grid frequency will arrive at its steady state around 200s.

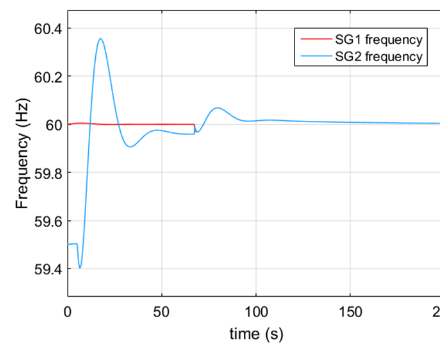


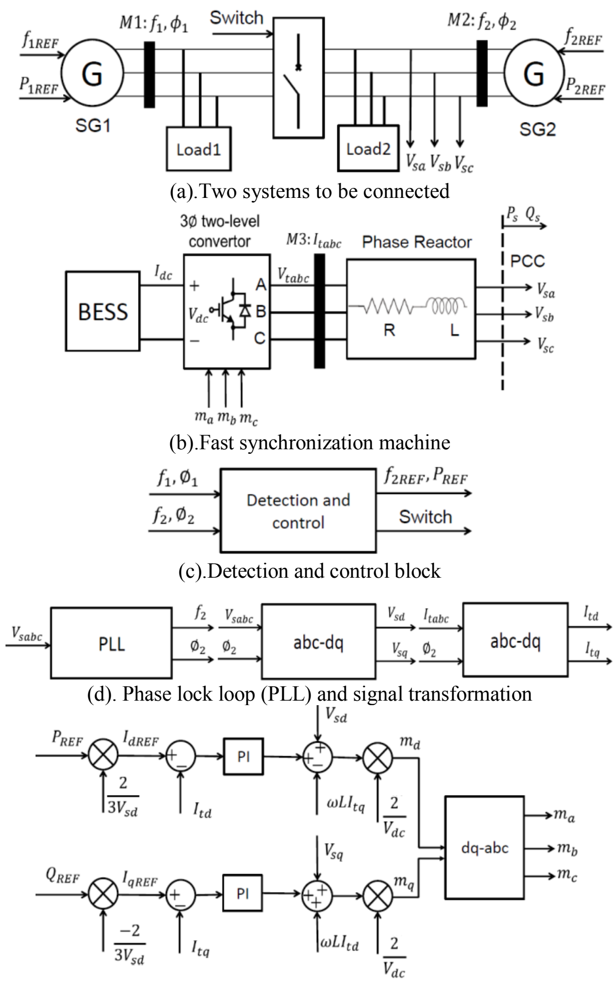
Fig.3. Frequency response of synchronous generators

Such synchronization speed might be tolerable when system events could be well predicted or prepared, and the synchronization windows were long enough for the primary and secondary controllers completing required actions. However, with the increasing penetration of renewables, future power grids are more vulnerable to resist sudden load/generation changes or other emergencies due to lesser inertia. If a required grid reconfiguration could not be achieved in a timely manner, the stability and efficiency of power systems might not be maintained. Therefore, fast synchronization is of critical importance for the stable and efficient operation of future power grids.

III. PROPOSED FAST GRID SYNCHRONIZATION METHOD

As discussed in Section II, the rotor speed of a synchronous generator can be adjusted by changing the mechanical inputs into the generator and electrical outputs from the generator. Because BESS has the capability to absorb or supply powers to the grid, it can be used to adjust the power injections of a generator or grid to adjust the corresponding rotor speed or grid frequency. Therefore, a fast synchronization can be achieved through quickly adjusting absorbing or supplying powers of BESS if it is connected with the grid.

Fig. 4 gives the schematic for the proposed fast synchronization machine. The synchronization machine is connected with one of AC grids. In Fig. 4, it is connected to System-2. This machine consists of a BESS, a two-level voltage source power converter, and a detection and control block. The integration of voltage source converter and BESS can provide required amount of power to the AC grid, which achieves the goal of dynamic power compensation to AC system. Therefore, the fast synchronization machine can regulate the frequency of the corresponding compensated grid and close the switch in a short time.



(a).Two systems to be connected

(b).Fast synchronization machine

(c).Detection and control block

(d). Phase lock loop (PLL) and signal transformation

(e). Power converter control

Fig.4. Schematic of fast synchronization machine

A. *BESS Modeling and Specification*

As an essential part of the fast synchronization machine, BESS supplies or absorbs energy during synchronization process. It is assumed that a lead-acid battery is used by the BESS. Its discharging and charging dynamics can be modeled as (4) and (5), respectively:

$$V_{batt} = E_0 - R\cdot i - K\frac{Q}{Q-it}\cdot(it+i^*) + Exp(t) \tag{4}$$

$$V_{batt} = E_0 - R\cdot i - K\frac{Q}{it-0.1\cdot Q}\cdot i^* - K\frac{Q}{Q-it}\cdot it + Exp(t) \tag{5}$$

where V_{batt} is the battery voltage (V), E_0 is the battery constant voltage (V), K is the polarization constant (V/Ah), Q is the battery capacity, $it = \int idt$ is the actual battery charge (Ah), R is the internal resistance (Ω), i is the battery current (A), and i^* is the filtered current (A).

This model is based on the assumption that the internal resistance is kept constant during the charging and discharging cycles and does not vary with the amplitude of the current. For the discharging process of the battery, its working zones can be classified into exponential zone, nominal zone, and depletion zone. In order to achieve ideal performance of the fast synchronization machine, we need to guarantee that the battery works in the nominal zone.

In order to meet the power requirements of the fast synchronization machine, the parameters of battery should be carefully selected:

State of charge (SOC) is defined as the percentage of the energy stored in a fully charged battery. In order to keep a stable voltage output, the SOC should be kept between 20% and 90% during the synchronization process.

Battery capacity is the measure of a battery's capability to store and deliver electrical energy and in commonly expressed in units of ampere-hours. Based on the system demands, the battery should have appropriate capacity to finish the synchronization process. Since the synchronization machine only works in a short duration, the battery can be implemented with lower capacity.

Nominal voltage is defined as the output voltage of the battery working in the nominal zone. During the actual implementation of fast synchronization machine, the required nominal voltage of the system can be satisfied through series and parallel connection of battery units.

Battery response time represents the voltage dynamics and can be observed when a step current is applied. It is defined as the duration from the time that current applied to reach 95% of the final value. For the battery used in the fast synchronization machine, the response time should be able to facilitate the synchronization process, typically should not exceed 1/4 of the total synchronization time.

In this paper, the fast synchronization machine is tested on a high power rating synchronous generator. Therefore, the battery is configured with high nominal voltage, short response time and medium capacity, and the SOC is set at 80% to allow enough region of absorbing or extracting power. The battery configuration needs to be adjusted accordingly if different systems are tested, or different initial conditions are applied.

B. *Two-level grid-imposed voltage source power converter*

As displayed in Fig.4, BESS is connected to a 3-ϕ two-level voltage source converter, which is modulated to realize active and reactive power generation. The converter is composed of three identical half-bridge converters, and it can provide a bidirectional power-flow path between the battery and 3-ϕ grid. Assuming there is no ohmic voltage drop on switches, the terminal voltage of power converter is expressed as:

$$V_{t\{a,b,c\}} = m_{a,b,c}(t)V_{dc}/2 \tag{6}$$

In order to obtain 3-ϕ AC-side voltage and a balanced 3-ϕ line current, the modulation schemes must constitute a balanced 3-ϕ through closed-loop control strategy. The modulation signal can be described as:

$$m_{a,b,c}(t) = \hat{m}(t)\cos[\varepsilon(t) - 2\pi i/3] \tag{7}$$

where ε(t) contains the information of modulation frequency and phase angle, and $i \in \{0,1,2\}$.

For the control purpose of zero steady-state error, dq-frame strategy is applied to derive DC quantities of control variables [12]. The phase-locked loop (PLL) is utilized to extract the frequency and phase information of the controller. Each phase of the voltage source converter is interfaced with the grid via a series RL branch.

Voltage and current control modes are available for the instantaneous real and reactive power control between BESS and AC system. However, due to the shortcomings of no closed-loop control on the line current of voltage source converter, the voltage-mode control is not applicable in the AC system under the circumstance of frequent power command changes, which may experience large line current excursions. Therefore, the current-mode pattern is adopted here through controlling phase angle and amplitude of the converter line current with respect to the voltage at the point of common coupling (PCC).

The real and reactive power exchanged between voltage source converter and AC grid at the PCC are P_s and Q_s, and can be described in dq-frame as:

$$P_s = \frac{3}{2}\left[V_{sd}i_d + V_{sq}i_q\right],\ Q_s = \frac{3}{2}\left[-V_{sd}i_q + V_{sq}i_d\right] \quad (8)$$

In steady state, PLL guarantees that V_{sq} = 0. Then, the d−q axis reference currents are:

$$I_{dREF} = P_{sREF}\frac{2}{3V_{sd}},\ I_{qREF} = -Q_{sREF}\frac{2}{3V_{sd}} \quad (9)$$

Under the condition that PLL contributes the same frequency and phase as $V_{s\{a,b,c\}}$, the space form of the converter model can be represented in dq-frame as:

$$L\frac{di_d}{dt} = L\omega_0 i_q - Ri_d + V_{td} - V_{sd},\ L\frac{di_q}{dt} = -L\omega_0 i_d - Ri_q + V_{tq} \quad (10)$$

Based on the dq-frame modeling of power converters, explicit control schematic is shown in Fig.4. The control scheme generates the modulating signals in dq-frame, which can be further transformed into abc-frame to modulate switches. Finally, with the current-mode control of the voltage source power converter, the power exchanged at PCC is equivalent to the preset reference power.

C. Operating Mechanism of Fast Sychronzization Machine

The operating mechanisms of the BESS and converter based synchronization machine are embedded with the detection and control block in Fig.4. Using the proposed method, the entire synchronization process can be classified into three stages, including fast frequency compensation stage, phase matching stage, and post switch-closing stage.

During the fast frequency compensation stage, the synchronization machine delivers or absorbs large amount of power to or from the grid to gain a quick change on system frequency. Then, the machine working status shifts to the phase matching stage. During this stage, the frequency of the compensated system is regulated, which slightly deviates from the nominal frequency. When the automatic power compensation controller makes phase matching at the end of this stage, then the switch is closed. After closing the switch, the synchronization machine provides automatic-controlled power to the two connected system, which helps to damp the frequency oscillations and stabilize the system frequency.

The detailed operating mechanism for each stage of synchronization process will be demonstrated through an example in next section.

IV. Performance and Simulation of Proposed Fast Synchronzation Method

The proposed method is implemented and tested on two synchronous generator-based AC grids in MATLAB/Simulink environment. The system configurations are given in Fig.1 and Fig. 4. The parameters of two systems are given in Table I, and the initial conditions of BESS are listed in Table-II. The parameters for generators are taken from the example 3.1 and 3.2 in [9]. The performances of the fast synchronization machine under three different stages are summarized below to demonstrate the effectiveness of proposed synchronization mechanism.

TABLE I: Parameters of Two Unsynchronized AC Systems

	Active Power	**Reactive Power**	**Frequency**	**Line-to-line Voltage**
System-1	150 MW	20 MVar	60 Hz	13.8 kV
System-2	150 MW	10 MVar	59.5 Hz	13.8 kV

TABLE II: Initial Conditions of BESS

Nominal Voltage	**SOC**	**Rated Capacity**	**Battery Response Time**	**Nominal Discharge Current**
30.36 kV	80%	10 Ah	1.0 s	200 A

A. Fast frequency compensation stage

The synchronization machine is attached to System-2. In this stage, it delivers a large amount of electric power to System-2 at the PCC, and then causes a quick frequency increase at System-2 as shown in Fig.5. Such power compensation is equivalently to reduce the load of System-2. In Fig.5, the frequency increase is occurring at time t_0 = 1.5s.

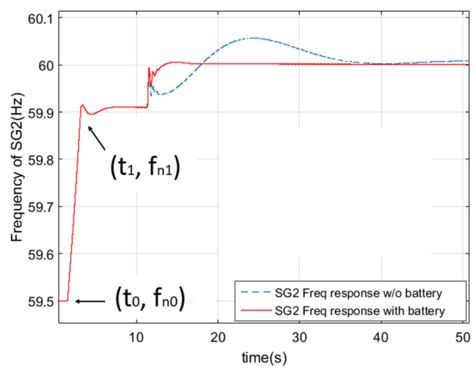


Fig.5. Frequency response of synchronous generator 2

As we can refer from (3), the mechanical power cannot change significantly in a short time because of the slower dynamics of the primary controller. Therefore, the frequency of System-2 will change approximately linearly during the fast frequency compensation stage. Then, (3) can be rewritten as

$$\Delta\omega = \left(P_m - P_e + P_{comp}\right)\Delta t / \left(J\omega_0\right) \quad (11)$$

where $\Delta\omega$ is the frequency deviation in a period of time Δt, and P_{comp} is the compensated power supplied by the fast synchronization machine. Before connecting the synchronization machine to System-2, the AC grid works in a steady state, which means $P_m = P_e$. Then, the system can reach the desired frequency, f_{n1} after a period of time, Δt:

$$f_{n1} = f_{n0} + P_{comp}\Delta t / \left(J\omega_0\right) \quad (12)$$

In this testing case, f_{n0} = 59.5Hz, f_{n1} = 59.91Hz, P_{comp} = 5MW and Δt = 1.65s. At time t_1 = 3.15s, the frequency of

System-2 arrives at the phase matching point, which is denoted as f_{n1} in (12). During the fast frequency compensation stage, the BESS is continuously supplying power to the grid until the phase matching point is reached.

B. Phase matching stage

In this stage, the frequency reference of SG2 is adjusted, and the automatic power compensation controller is applied to match the phase. After time t_1, the system needs to maintain the frequency at f_{n1}. However, f_{n1} starts to drop because of the dynamics of the governor. In order to keep the phase matching frequency, the frequency reference should be changed and the automatic power compensation controller should be utilized. The schematic of automatic power compensation controller is displayed in Fig.6.

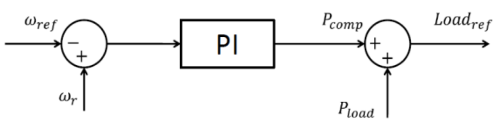


Fig.6. Automatic power compensation controller

Due to the fact that $P_m \neq P_e$ if battery is removed after time t_1, the automatic power compensation controller is activated at this time to provide the desired power to the grid, which guarantees that $P_m - P_e + P_{comp} = 0$ in (13):

$$J\, d\omega / dt = \left(P_m - P_e + P_{comp}\right) / \omega_0 \tag{13}$$

The output of automatic power compensation controller supplies dynamic electrical power, which counteracts the dynamics of mechanical power. Through the compensated power of BESS, frequency requirements of $d\omega/dt = 0$ and $\omega_r = \omega_{ref} = f_{n1}$ are satisfied. In order to close the switch, the frequency deviation between two AC systems should be satisfied with IEEE 1574 standards. The frequency of System-2 holds at f_{n1} to wait for the phase matching with System-1.

As shown in Fig.7, the phase matches at time t_2= 11.3s. Then, the switch closes after time t_2. The entire process takes less than 10s ($t_2 - t_0$= 9.8s), which is significantly less than the traditional synchronization method as shown in Fig. 3.

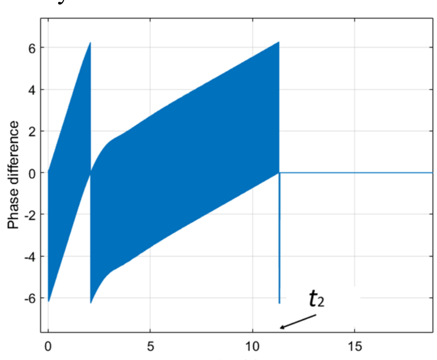
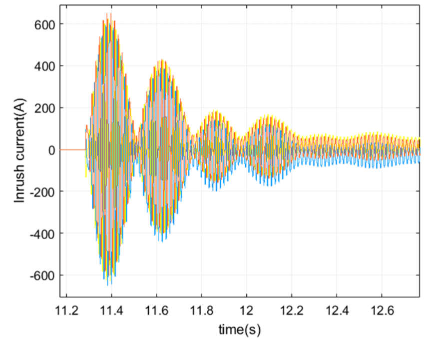


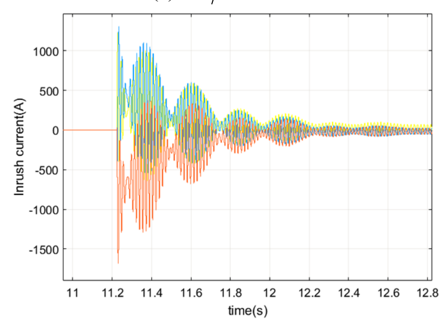
Fig.7. Phase difference between two systems

C. Post switch-closing stage

In this stage, the in-rush current on the tie line between systems is monitored, and the automatic power compensation controller is also utilized to damp frequency oscillations caused by phase and frequency difference before the closing. During phase matching stage, the frequency f_{n1} is kept at a fixed magnitude, which allows the phase difference between two systems can be reduced and reach a tolerable smaller value at the end of the stage. After closing the switch between two systems, the in-rush current flows on the tie line and frequency oscillations will be monitored, and the corresponding results for the testing case are given in Fig.8 and Fig.9, respectively.

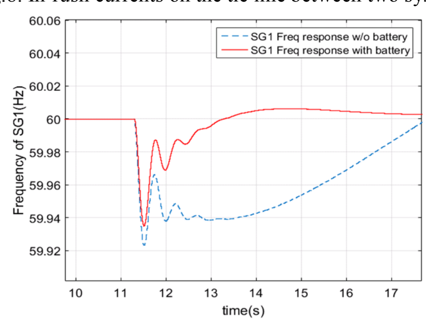


(a). $\Delta\phi = 0.01^0$

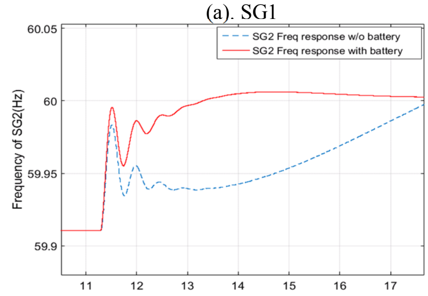


(b). $\Delta\phi = 2^0$

Fig.8. In-rush currents on the tie line between two systems



(a). SG1



(b). SG2

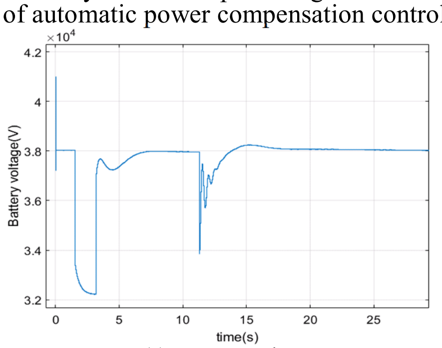
Fig.9. Frequency responses of generators after closing the switch

Fig.8 gives the in-rush current results obtained by two scenarios that have different phase differences, but same frequency difference between two systems at the moment of switch closing. As shown in Fig. 8, the after-closing inrush currents are depending on the before-closing phase difference. The in-rush current can be minimized if the phases between the systems are exactly matched before closing. In addition, during the simulation we also found that the phase difference has a superior impact on the magnitude of in-rush current than the frequency difference. After closing the switch, the automatic power compensation controller is continuing to be used to generate the electrical power to stabilize the system frequency at f_{n2} = 60Hz. The only difference for the usage of automatic power compensation controllers between phase matching stage and post switch closing stage is that the referenced frequency is set as ω_{ref} = 60Hz in the post switch closing stage, but ω_{ref} = 59.91Hz in the phase matching stage.

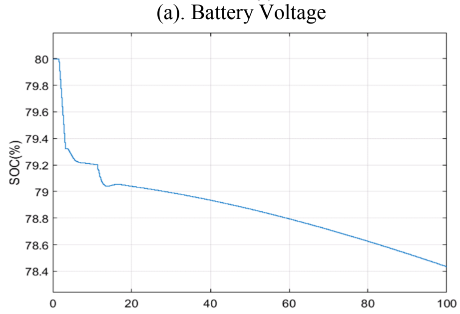
Fig. 9 demonstrates the frequency oscillation damping effect provided by the BESS. In Fig.9, the blue dashed line represents the frequency behavior without the support of BESS in the post switch closing stage, while the red solid line stands for the frequency response with BESS participation. It is obvious that the BESS-based fast synchronization has the capability to damp the oscillations and improve the stability of systems.

D. Dynamic response of the battery

Fig.10 shows the dynamics of battery voltage and SOC during the synchronization process. During the fast frequency compensation stage, the battery produces significant amount current to compensate the power requirements of AC systems. While in the phase matching and post switch-closing stages, the battery continues providing the currents to meet the needs of automatic power compensation controllers.



(a). Battery Voltage



(b). Battery SOC

Fig.10. Voltage and SOC dynamics of the battery

As demonstrated by the results of voltage dynamic response, the battery used by the fast synchronization machine should have a fast enough response to the variations of output current. Selecting an appropriate battery for the fast synchronous machine is of critical importance for the proper functioning of the proposed fast synchronization mechanism. The key factors for battery selection are the nominal current magnitude and voltage response time. In addition, maintaining a reasonable level of SOC is also important for overall performance of the synchronization machine. In the testing case given in this paper, the frequency of the regulated synchronous generator is lower than the nominal frequency, so the AC system always extracts power from the battery. However, if the regulated generator works with a frequency higher than the nominal value, the battery needs to absorb power from the AC system. Based on the bidirectional power transfer characteristic of the battery, we suggest the SOC should maintain a level between 30% and 80% before starting the synchronization process.

V. CONCLUSIONS

This paper proposes a novel method to realize fast synchronization between two AC grids through a fast synchronization machine, which integrates a BESS with a grid-imposed voltage source power converter. The fast synchronization machine can extract or absorb desired amount of real and reactive power from or to the AC grid. Therefore, the frequency and phase of the AC grid can be regulated in a timely manner through power compensation from the fast synchronization machine. The preliminary simulation results given in this paper has shown that the proposed fast synchronization method can reduce the synchronization time by an order of magnitude compared with tradition methods.

Future work will be focused on improving the proposed method with more synchronization parameters (such as voltage magnitude), investigating the influence of fast frequency changes (during battery support) on other devices (such as drives, and DG), and conducting some scaled down experimental validation.

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