Rapid Synchronisation Procedure for a Pneumo-Hydraulically Driven Synchronous Generator

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***Abstract*—When an under-frequency event occurs in a power network, additional power must be delivered by employing instantaneous reserves. Globally, such reserves are usually supplied by thermal generation sources, which incur no-load running costs due to mechanical and electrical losses. To avoid these losses, a generator should be maintained at rest. When the system is triggered, the generator must then be rapidly accelerated and connected to the power network. This paper presents a cost-effective environmentally friendly energy storage system at the 100 kW - 1 MW scale which can provide distributed frequency support during contingent events in a grid.**

The presented system is a small-scale compressed air energy storage system which employs a hydraulically driven synchronous generator. In order to synchronise the proposed device with a power grid, a novel control approach has been developed for the acceleration stage. We present computational results which model the performance of this control approach for a prototype system, and show that, in principle, synchronisation of both phase and velocity can be achieved in $<$ 0.7 s. The proposed system intended to provide high-power short duration discharge and maintain its power supply for 1 - 15 mins.

I. Introduction

Penetration of intermittent energy sources in New Zealand will lead to an increased requirement on the power network in terms of frequency regulation [1]–[3]. Frequency stability is an imperative aspect of stable network operation since severe frequency droops can lead to cascade failures [4]. Under-frequency events occur when demand exceeds generation, and the System Operator must respond rapidly to prevent cascade failure - either by increasing generation or reducing demand. The available rapidly switchable sources of demand and generation are termed "instantaneous reserves" (IR), and traditionally comprise "interruptible load" (IL) [3]–[6] and "spinning reserves" (SR) [4], [5], [7]–[12]. Internationally spinning reserves are usually supplied by thermal generation sources which incur no-load running costs.

It is well known that the overall stability of a power grid containing renewable energy sources, can be improved by incorporating Electrical Energy Storage (EES) systems within the network [7], [10], [13]–[16].

For instance, one large-scale technology available in this market is Compressed Air Energy Storage (CAES). Such plants represent mega-engineering projects ($>$ 100 MW), and exhibit start-up times of $\sim$ 5 - 10 mins. Conventional CAES systems require the availability of large underground geological caverns, which is not generally conducive to widespread installation in a transmission network. However, this can be addressed by using above-ground pressure storage vessels, thus making this approach suitable for mobile energy storage systems. In this paper a novel modular Small-Scale Compressed Air Energy Storage System (SS - CAESS) will be investigated as the most suitable solution for the above described challenge.

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II. System overview

Fig. 1 shows a schematic of the SS - CAES system that is the subject of this study. In this system, energy is stored in a form of a compressed gas within a hydraulic accumulator. In case of a contingent event, this energy is released and pressure applied to a non-compressible hydraulic fluid [17], rapidly accelerating the generator to synchronous speed. The ability to start up from rest enables lower operating costs, as this approach does not incur inherent I^2R and other losses that occur during condenser operation.

Measured frequency and phase data from both the grid and the generator, is used to implement feedback control of the hydraulic system, which computes and controls the required acceleration trajectory of the generator.

The aim is that the generator phase should be accelerated to follow a computed ballistic trajectory that leads to simultaneous synchronisation of both frequency and phase. In the case considered here, it is required that within 1 s after start-up, the generator be synchronised to all 3 grid parameters: frequency, phase angle and voltage. Several processes must happen simultaneously for this to be achieved. The hydraulic motor spins the shaft of the generator from rest when the system is triggered, with the speed and frequency of the generator determined by the hydraulic flow.

At the same time, the AVR system energises the field windings of the generator so that the generator terminal voltage which will match the grid voltage. The most important parameter in this process is the control system output which drives the solenoid of the proportional throttle valve. This regulates the pressure drop across the motor, and the torque

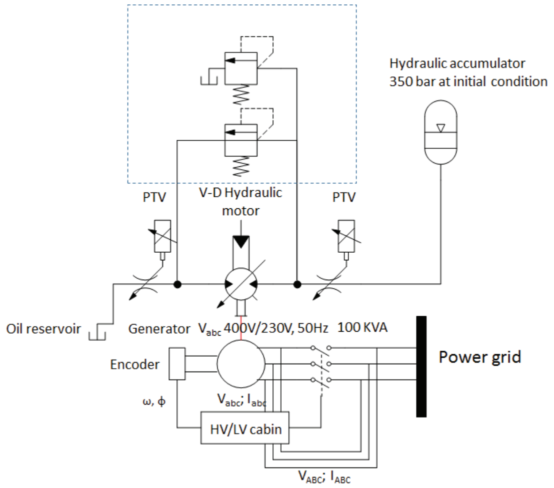


Fig. 1: Simplified block diagram of the prototype [17], [18].

on the generators shaft hence enabling the motor speed and acceleration to be controlled. At the moment at which phase and frequency are matched, the electrical connection between the generator and grid must then be closed. It is necessary for the generator and grid to maintain synchronisation until the circuit breaker is fully closed - posing a potential challenge for the proposed pneumo-hydraulic system. Typical closing times of mechanical circuit breakers are $>$ 50 ms, although solid-state IGBT breakers can achieve much shorter switching times. However IEE certified solid state breakers are expensive, adding to the overall system cost.

A hardware prototype of our proposed pneumo-hydraulic system has been designed and built. The 100 kW prototype has been designed to fit within a standard 20 ft shipping container which provides both transport and a safety enclosure for the high pressure ($>$ 200 bar) hydraulic machinery. The modelling presented here has informed key design choices for this prototype. Key components include:

A. Synchronous Generator

A 4-pole synchronous generator (ABB AMG 0250DD04, 100 kW, 400V/230V, 50 Hz), is directly coupled to the shaft of the hydraulic motor. The generator terminals are connected to the power grid via a circuit breaker. The field windings of the generator are energized by an Automatic Voltage Regulator (AVR).

B. Hydraulic Accumulator

A hydraulic accumulator stores gas under pressure. When the system is triggered, this energy is released, driving fluid through the hydraulic circuit [16].

C. Proportional Throttle Valve

A soft-shift spool controls the pressure drop between the valve ports. The spool displacement is proportional to an applied DC control voltage [19], [20].

D. Variable - Displacement Hydraulic Motor

Torque is delivered to the generator by a hydraulic motor, comprising several cylinder pistons, formed around a central shaft. The hydraulic displacement of this motor can be changed by varying the inclination of a swashplate connected to the pistons. This makes it possible to maintain a constant torque on the generator, even as the accumulator pressure decreases during discharge [21].

III. Acceleration approach

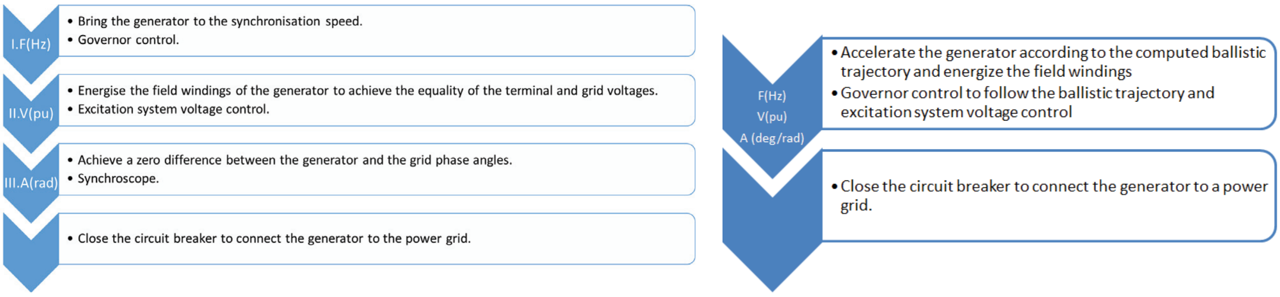
Design of the acceleration and synchronisation approach is the most important and difficult part of the proposed device's design. Within New Zealand, the provision of instantaneous reserve requires that the generator can be connected to the power grid within 1 - 6 s. The conventional procedure to synchronise a generator to a power grid is depicted in Fig. 2(a). The use of this methodology means that it is possible to reach the best moment for synchronisation of a generator and a grid, however, it does not minimise the time to reach this state, and typical synchronisation times are $>$ 5 - 7 s. Instead, we have proposed and adopted a modified synchronisation procedure as shown in Fig. 2(b).

Belyaev et al. [22] has described a related synchronisation technique based on a reference model, but the presented results do not achieve synchronisation to a grid within 1 s. In addition, ref. [22] does not discuss damping control, and states that the voltage magnitude is usually provided by AVR without any complications. Simulation of a contingent event is also presented, however the droop rates considered (-0.3 Hz/s) are substantially less than the rates studied here (up to -2.0 Hz/s). Such rapid droop rates are known to occur in small islanded networks such as that found in New Zealand. For instance, the HVDC bipole trip on the South Island which occured on 21 September 2015 (-1.4 Hz/s) [4]. Based only on one example in [22] it is difficult to verify feasibility and robustness of the described there approach.

Rapid start-up of a synchronous generator is challenging, due to the rapid acceleration required of the entire rotor inertial mass. Feedback control should be implemented, which will minimise the start-up time from the at rest initial condition and avoid current-spiking from the generator. Overall, the demand trajectory for the acceleration stage (ballistic trajectory) is based on calculating a fixed shaft torque such that the error between the grid and the generator phase angles is zero at the moment when the generator's frequency matches the grid's frequency [23]. This method is depicted in Fig. 2(b).

By employing the proposed strategy, it is possible to fulfil the requirements I and III of the conventional synchronisation procedure. The equality of the voltage magnitudes of a grid and a generator (requirement II) is achieved by employing the excitation system which is installed in the prototype.

A visual depiction of this method is presented in Fig. 3. A constant phase point for the different grid cycles are represented as the diagonal lines displaced by 2π along the phase axis. The system is triggered at 1 s, followed by acceleration of the generator. When the generator's acceleration



(a) Conventional synchronisation procedure

(b) Ballistic approach

Fig. 2: Synchronisation procedure for a synchronous generator. (a) Conventional synchronisation procedure. (b) Proposed ballistic approach

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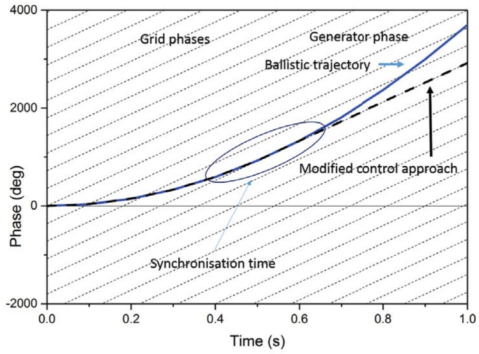


Fig. 3: Visual description of the synchronisation method used in our proposed system.

trajectory tangentially intersects one of the 50 Hz grid cycles, synchronisation occurs. This moment represents the equality of both the phase and the frequency, so the circuit breaker can connect the generator to the power grid [22].

The optimal acceleration to guarantee zero phase and frequency error between the grid and the generator at T_{sync} is given by 1 [23] and depicted in Fig. 3 as the solid line:

$$\alpha_{opml} = \frac{1}{2}\frac{\omega_{s0}^2}{\theta_{g0} - (\theta_{s0} - 2n\pi)} \quad (1)$$

The $2\pi n$ determines which electrical cycle is selected for the synchronisation target, and this choice defines the optimal acceleration, $\omega_s(t)$ is the grid speed as a function of time t (rad/s), θ_{g0} and θ_{s0} are the grid phases sampled at the current time t_0 (rad). The dash line in Fig. 3 represents the modified ballistic approach that potentially can be used in order to employ a mechanical contactor in the system. This method increases a synchronisation window, hence makes possible the use of a mechanical circuit breaker (regardless of its delay).

IV. Modelling Results

The performance of the system is simulated by employing a Matlab Simulink model. The simulations shown here focus solely on the initial acceleration process following triggering in response to an under-frequency event. Fig. 4 shows a visual representation of the simulated system behaviour, whereby once the generator speed is matched to the grid, the phase of the generator is also synchronised and then continues to follow the grids phase. From the expected acceleration rate of the rotor, the control system computes the optimal target phase for synchronisation. If the calculated acceleration trajectory cannot satisfy all the requirements for synchronisation, the control system can slip back by 2π cycle in order to find another target phase. This behaviour continues until the phase error is equal to zero, at the computed future synchronisation moment. The phase increment for the simulation has been chosen to equal 1and the results are depicted in Fig. 5. The vertical negative slope represents the time which is required for the control system to slip back a full cycle (2π), in order to find the target grid cycle for synchronisation. We have run a series of simulations using this control model to explore the effect of different frequency droop rates and the initial phase of the generator shaft, from which a number of graphs have been plotted to verify the robustness of the control system. Fig. 6 portrays the time for synchronisation of the generator with a power grid. The lower boundary represents the moment when the generator phase enters the synchronisation window, which is defined as the period during which the generator frequency is within $\pm$ 0.3 Hz of the measured grid frequency. The upper boundary denotes the time when the generators phase subsequently exits the synchronisation window i.e. the generator frequency exceeds the grid frequency by more than 0.3 Hz [24].

Hydraulic control should maintain the synchronisation window for long enough that the electrical connection between the generator and grid can be closed. Fig. 7 shows the calculated time duration of the synchronisation window for each droop rate considered, which is in the range 5.5 - 8.5 ms in all cases. This is substantially shorter than typical connection (closing) times which can be achieved using mechanical contactors (typically $>$ 50 ms). This means that, if a control signal is send to the breaker when the trajectory hits the lower phase boundary, the contactor will not be able to connect the generator to the grid before the generator moves out of

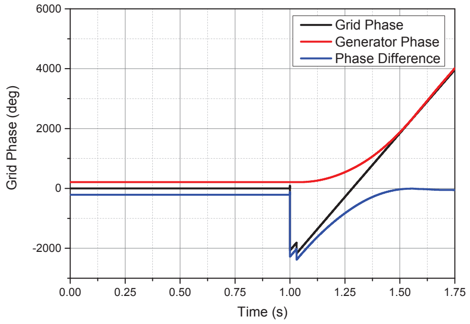


Fig. 4: Simulink modelling results of the generator and the grid phases following an event to trigger rapid start-up and grid synchronisation by employing the modified computer model.

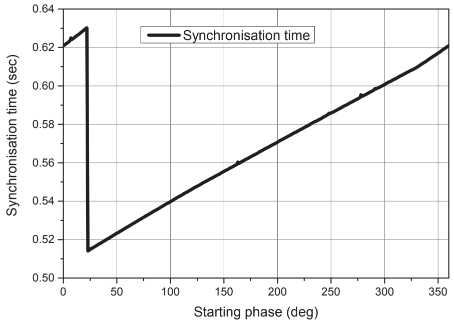


Fig. 5: Simulation results of synchronisation time with the increment equals 1°.

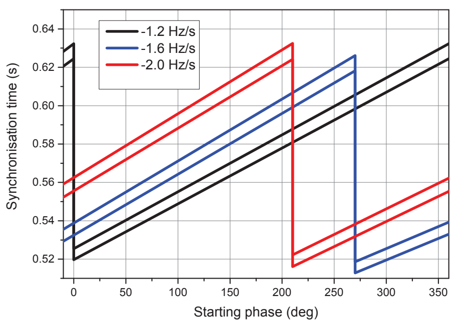


Fig. 6: Lower and upper time boundaries for synchronisation within the different frequency decrease rates.

synchronisation with the grid (because of the switching delay). The most feasible solution in this situation is the use of a solid - state switch (on IGBT transistors, for instance), which can achieve switching times $<$ 1 ms.

The last synchronisation requirement (after phase and frequency) is that the voltage amplitude of the generator and grid are also equal. Depiction of this requirement is also the easiest way to present the transient effects which occur following

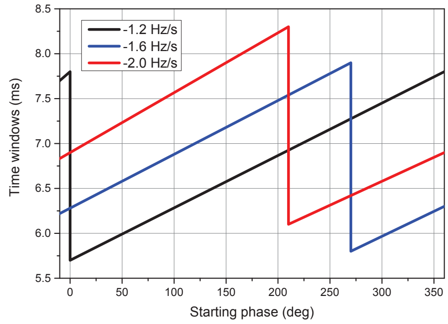


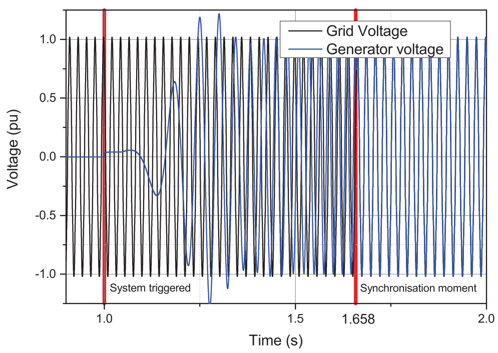
Fig. 7: Time windows for the synchronisation moment with the range $\pm$ 0.3 Hz.

the generators connection to the grid. The plots are presented in Fig. 8 and depict the zoomed positive magnitudes of the sinusoidal voltage waveforms (only phase C is shown). The horizontal lines represent different synchronisation boundaries for the voltage based on the manufacturers recommendations for the generator ABB AMG-0250. The recommended voltage error is 2% (1.02 - 0.98 pu), the maximum tolerable value is 4.5% (1.045 - 0.955 pu). The maximum allowed voltage error according to the IEEE 1547 Standard [24] is 10% and this is also shown in Fig. 8. It can be seen that the voltage peaks lie within the 2% range at all times $>$ 0.5 s after being triggered, fulfilling this requirement prior to synchronisation of phase and frequency. Reassuringly, this voltage behaviour is achieved using a Standard excitation system mathematical model. Similar successful results for voltage matching were achieved at different frequency droop rates and different initial rotor angles of the generator.

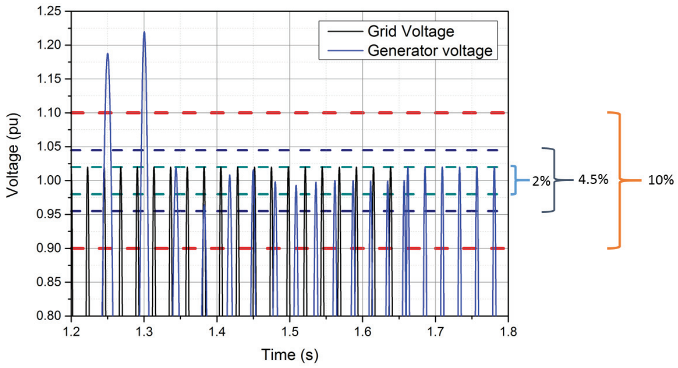
V. Conclusion

We have developed a computational model which describes the transient processes occurring during the rapid start-up acceleration of the system under study, and implemented a novel control approach which targets a ballistic acceleration trajectory that enables frequency, phase and voltage to be simultaneously synchronised. We have studied the robustness of this control approach as a function of the starting position of the generator and the frequency droop rate of the grid. From this, we have obtained synchronisation time plots in correlation to the various frequency droop rates.

We find that the present control approach delivers synchronisation windows which are too short (5.5 - 8.5 ms) to enable a mechanical circuit breaker to be fully closed, and further work is required to investigate modified control approaches that can lengthen this window. The implemented modifications will control the acceleration of the generator and slows it down (or in some cases accelerate it), to keep the generator phase within the range of $\pm$ 0.3 Hz from the tangent intersection with the grid phase. It increases the synchronisation windows, hence will give the opportunity to close the circuit breaker while the frequencies and phase angles between the generator



(a) Full peak-peak waveform



(b) Magnified votlage plot

Fig. 8: Terminal and grid voltage plots. (a) Full peak-peak waveform. (b) Magnified votlage plot
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and the grid are equal. A second possible option is to employ a circuit breaker based on IGBT transistors or other power electronics switch devices and this is also a matter for future investigation.

Nonetheless, our simulations have shown that the proposed ballistic trajectory control approach, will enable the proposed 100 kW prototype to fulfil all the requirements for synchronisation within 0.5 - 0.7 s after being triggered. This would enable this device to operate as a Fast Instantaneous Reserve in a power grid, with a connection time of < 1 s after triggering, which is equivalent to most forms of interruptible load.

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REFERENCES

[1] AEA, "Energy Storage and Management Study," Scottish Government ELL/000/077, Ayshire, Tech. Rep., 2010.
[2] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical Energy Storage for the Grid: A Battery of Choices," *Science*, vol. 334, no. 6058, pp. 928–935, nov 2011. [Online]. Available: http://www.sciencemag.org/cgi/doi/10.1126/science.1212741
[3] NZ Electricity Commission, "Summary report: Effect of large scale wind generation on the operation of the New Zealand Power System and Electricity Market," p. 48, 2007. [Online]. Available: https://www.ea.govt.nz/dmsdocument/1876
[4] System Operator, "Automatic Under-Frequency Load Shedding (AUFLS) Technical Report," Transpower, Tech. Rep., 2010.
[5] Electricity Commission, "Current Arrangements for Frequency , Voltage , Reliability and Security," Tech. Rep., 2007.
[6] Whole Advisory Group, "National Instantaneous Reserve Market," Tech. Rep., 2013.
[7] D. Rastler, "Electricity Energy Storage Technology Options," Electric Power Research Institute, Palo Alto, Tech. Rep., 2010.
[8] Transpower, "Effect of wind generation on management of frequency excursions," Tech. Rep., 2007.
[9] A. Akele-sita and S. Chowdhury, "Optimal allocation of energy storage in a future congolese power system," in *50th International Universities Power Engineering Conference (UPEC)*. IEEE, sep 2015, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7339933
[10] C. Schaber, P. Mazza, and R. Hammerschlag, "Utility-Scale Storage of Renewable Energy," *The Electricity Journal*, vol. 17, no. 6, pp. 21–29, jul 2004. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1040619004000594
[11] T. R. Ayodele and A. S. O. Ogunjuyigbe, "Mitigation of wind power intermittency: Storage technology approach," *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 447–456, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2014.12.034
[12] H. Chen, T. Ngoc, W. Yang, C. Tan, and Y. Li, "Progress in electrical energy storage system : A critical review," *Progress in Natural Science*, vol. 19, no. 3, pp. 291–312, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.pnsc.2008.07.014
[13] Anon, "Fire Resistant Hydraulic Fluids," *Lubrication*, vol. 48, no. 11, pp. 161–180, 1962.
[14] J. Eyer and G. Corey, "Energy Storage for the Electricity Grid : Benefits and Market Potential Assessment Guide," Sandia National Laboratories, Albuquerque, Tech. Rep. February, 2010.
[15] J. Baker, "New technology and possible advances in energy storage," *Energy Policy*, vol. 36, no. 12, pp. 4368–4373, 2008.
[16] P. J. Hall and E. J. Bain, "Energy-storage technologies and electricity generation," *Energy Policy*, vol. 36, no. 12, pp. 4352–4355, 2008.
[17] E. Sturov, Y.-Y. P. Chen, A. Wood, R. Rayudu, R. Badcock, and C. Bumby, "Rapid start up and synchronization of a hydraulically driven synchronous generator," in *EEA Conference & Exhibition, 22-24 June*, Wellington, 2016.
[18] ——, "Rapid synchronization procedure for a synchronous generator employing ballistic trajectory control," in *ISGT PES 2016 Asia*, Melbourne, 2016.
[19] F. Norvelle, *Elecrohydraulic Control Systems*. New Jersey: Prentice Hall, 2000.
[20] B. Trinkel, "Fluid Power Circuits Explained, Chapter 14: Proportional Throttle Valves," 2007. [Online]. Available: http://hydraulicspneumatics.com/other-technologies/book-2-chapter-14-proportional-control-valves
[21] D. Dunn, "Unit 24: Applications of Pneumatics and Hydraulics," p. 14. [Online]. Available: http://www.freestudy.co.uk/fluid power/motors.pdf
[22] N. A. Belyaev, Y. V. Khrushchev, S. V. Svechkarev, A. V. Prokhorov, and L. Wang, "Generator to grid adaptive synchronization technique based on reference model," *2015 IEEE Eindhoven PowerTech, PowerTech 2015*, 2015.
[23] Y.-Y. P. Chen, "Rapid Synchronization Control of Compressed Gas Energy Storage Generator During Power Grid Contingent and Extended Contingent Events," M.S. thesis, University of Canterbury, 2015.
[24] IEEE Standards, "IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems," New York, p. 27, 2003.