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Adding Inertia to Isolated Power Systems for 100% Renewable Operation

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Abstract

Following time-constraining obligations under 2015 Paris Agreement, nations are racing to integrate more renewable energy generation into their power systems than ever before. While solutions for mitigation of renewable energy negative effects to power system stability exist, they are still complex and expensive. One of the most promising technologies, battery energy storage, is widely advocated, but is still unable to solve basic challenge of renewable energy integration – low inertia and provision of sufficient fault currents. This paper presents a practical enabling technology in a form of synergy between a battery energy system and a synchronous machine, which can support fully renewable power system while providing nominal power system inertia. For simplicity, the case for this technology is presented on an example of an Isolated Power System capable of 100% instantaneous renewable operation for prolonged periods of time. High-speed measurements during both steady-state operation and performance under fault conditions were recorded and presented in the paper.

Keywords: Inertia, Isolated Power Systems, Microgrids

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1. Introduction

With the adoption of 2015 Paris Agreement, nations around the world set out targets for the reduction of greenhouse gasses (GHG) emissions, and with it, plans for transition to renewable energy (RE) power systems. Some nations, such as Pacific countries, are directly threatened by raising sea levels and have decided to set bold RE goals, aiming for 100% RE power systems and GHG emissions reduction by 2050 by latest (although smaller nations aim to reach that goal by 2030).

Electricity consumers living on islands are not supplied from conventional interconnected power systems. These consumers are usually serviced by a local electricity generation and distribution system which we will refer to as an 'isolated power system' (IPS). Electricity in IPSs is traditionally generated using diesel generators which consume diesel fuel. Lately, IPSs started reducing GHG by integrating large-scale RE generation in their power systems. Unfortunately, RE from the two most abundant energy sources – wind and solar – incurs significant stability and reliability issues due to the intermittency of those sources.

IPSs are of interest for research of high RE penetration power systems and mitigating the risks of RE intermittency. Because a small investment can have a relatively large impact, the RE penetration in some IPSs has reached high levels (i.e. greater than 50%). It is no surprise then, that IPSs are at the forefront of research into enabling technologies for high RE power systems. A number or researchers have investigated problems caused by high RE penetration [1-3]. Most of the recent research focused on the role of inertia in power systems. More precisely, the inertia of wind turbine generators (WTG) and its effects on power systems [2, 3] was in the focus during the last decade. The effect of replacing conventional generation with WTG has also been widely discussed [1]. One of key lessons high RE penetration research in IPSs [4-8] has provided is that RE sources need complementary, or enabling, technologies to deal with the attendant issues of highly variable power output and low inertia. Examples of complementary technologies include: energy storage (e.g. battery [2], hydrogen, flywheels [3]), bio-diesel engines, fast acting demand response [6], better control systems [2]. While these technologies found their application, operation, maintenance and integration challenges still exist. Lately, advances in battery energy storage have shifted focus to this technology, more than any other. Control of batteries, or more precisely, inverters which connect battery storage to a power system was in research focus in the last decade. Advanced control strategies [9], synthetic inertia [10] and advanced inverter technologies [11] promise to solve the problem of low inertia in future RE power systems. Research has shown that inverters are capable complementing conventional generation in some cases, however, in power systems without conventional generation two main limitations of inverter technology are very much evident – no inertia, and low fault current provision capability.

The authors have worked in IPSs for a number of years, over which time we were exposed to some of the effects RE had on power system stability, and we were involved in day-to-day IPS operation. What we observed is that simple solutions, which mimic established routines, produce excellent power system results and are best received by power station operators. One of the best solutions introduced into IPS, was based on a synergy of new, fast acting battery energy system and almost a century old technology – synchronous machines.

2. Concept of the Synchronous RE generator

Stability of a power system relies on its generation to provide real and reactive power, provision of frequency and voltage control, provision of inertia, provision of fault currents and non-intermittent power supply. Modern research is pursuing improvements in inverter technologies, with goal of having a device capable of providing all the above power system services. Presently, this solution remains elusive, while nations are more aggressively pursuing higher RE penetrations, leaving power systems vulnerable to RE intermittency more than ever before.

2.1. Traditional governing of IPSs

IPS are traditionally powered by diesel generators (DGs). DG (Fig. 1 left) is a device which represents a synergy between a diesel engine (a) and a synchronous machine – alternator (b) which is connected to the grid. Positive side of DG technology is that it is a device capable of providing all necessary power system services to an IPS. Some of its characteristics are:

- Provides real power in range of 30 to 100% of its rated capacity [12],
- It can be overloaded of up to additional 10%, for limited periods of time,
- It can respond to a load step of up to 100% of its rated capacity,
- Engines could be started in under 10 seconds, provided they have been kept warm,
- Its synchronous machine can provide sufficient inertia and fault currents to an IPS, but
- They consume diesel fuel and are a source of GHG and frequent oil and fuel spills.

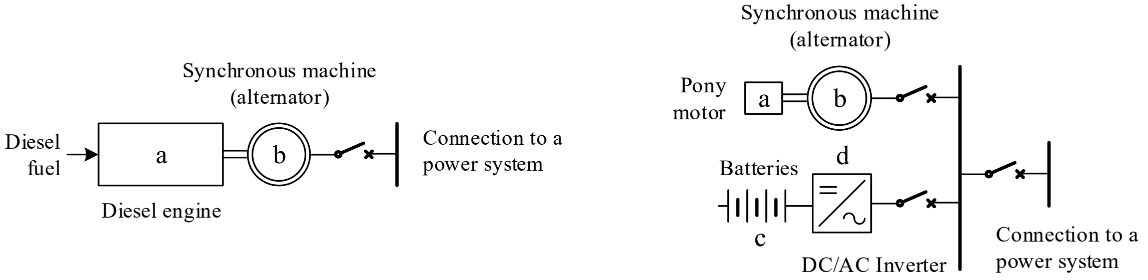

Fig. 1. (Left) Simple presentation of a traditional DG main components, and (Right) Simple presentation of a Synchronous RE generator main components

2.2. Proposed new Synchronous RE generator

If a battery energy storage is coupled with a synchronous condenser (SC), it forms a device which behaves like a synchronous RE generator (Fig. 1 Right). It consists of a synchronous condenser (such as described by [13]) (b), which is started by a small pony motor (a), batteries (c) and a DC/AC inverter (d).

Advantages of synchronous RE generator over a typical battery energy storage system lie in provision of system inertia and fault currents, services typical inverters cannot provide. Advantage of this technology over DGs is in utilization of stored RE and environmentally-friendly operation. Inverters usually have slightly higher overload capability than diesel engines, they can respond much faster than DGs and are able to operate in the entire 0 to 100% range compared to traditional DGs. Some of the limitations of Synchronous RE generator technology are:

- Complexity of the solution requiring sophisticated control system for control of two separate devices,
- Ability to operate in generation mode only when a battery energy storage has sufficiently high state of charge,
- Imposes a need for modestly higher skilled operation and maintenance crews.

3. Case study system and measurements

3.1. Case study system - King Island, Australia

Synchronous RE generator exists and operates in a real-world IPS on King Island (KI), in Australia. KI lies in the Bass Strait between Tasmania and the Australian mainland. It has a population of approximately 2,000 people, and an economy based on agriculture and food processing. Customer load on KI ranges between 1 MW and 3 MW, with an average of around 1.5 MW. The KI power system is shown in Fig. 2.

There is one power station on the island with four distribution feeders delivering electricity to customers. The power station houses four DGs with a total generation capacity of 5.8MW. Three fixed speed Nordex N29 (250kW each) wind turbines are installed on a nearby hill, together with two Vestas V52 turbines (850kW each) with doubly fed induction generators.

KI power station houses a 3 MWh advanced lead-acid battery [11]. Its 2 MW inverter is capable of controlling system frequency and voltage and responding to load step from 2 MW charging to 2 MW discharging within three cycles. Two SCs [14] installed in KI power station are rated at 1 MVA each. They use diesel engines for startup, after which diesels shut down and de-couple from alternators using a mechanical clutch. In addition, both SCs have a flywheel fixed to their shaft, which increases their inertia to about $H_{SC} = 15$ sec, which is well above the inertia of DGs in the system, which is nominally about $H_{DG} = 0.6$ sec [12].

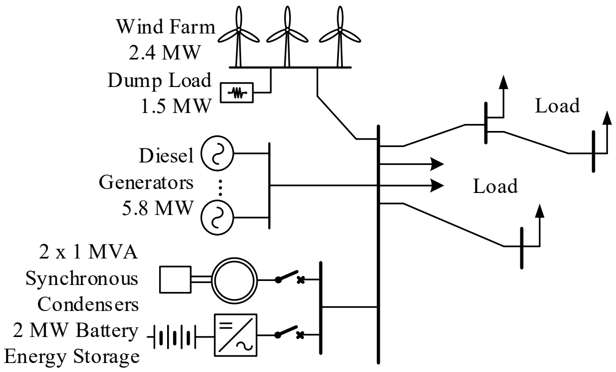

Fig. 2. Schematic representation of the King Island power system

3.2. Case study measurements

Here we present steady-state measurements and recorded performance of a synchronous RE generator during system faults from our case study system which demonstrate behaviour of the system with high RE penetration, in the presence of large-inertia SC and a BES system. KI power station has two data loggers; high speed measurements (at 1 kHz frequency) were taken using National Instruments (NI) CompactRIO instruments which are permanently connected directly to KI power station switchgear's current and voltage transformers. Additionally, station's control system records performance of KI power system using Allen Bradley Powermonitor 1000 devices, installed in each circuit breaker cubicle of the power station's switchgear, and samples at a frequency of 1 Hz. All measurements presented in our paper are during normal power station operation.

Fig. 3 (left) presents high speed measurements during a synchronisation of the SC to a power system run by one DG. The high-inertia SC synchronises to the grid at 60th second, system frequency becomes smoother, and the power system inertia increases.

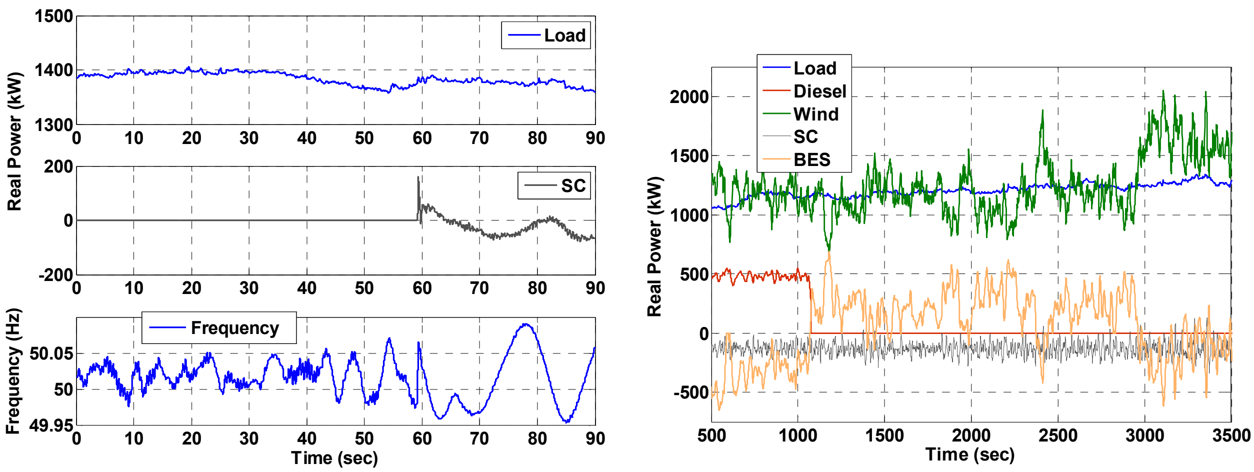

Fig. 3. (Left) Measurement data showing synchronisation of a Synchronous Condenser (SC) to the grid, and (Right) Measurement data for transition into fully renewable generation

Fig. 3 (right) presents power system operation during high RE penetration after the shutdown of the last DG. During the period presented in Fig. 3 (right), RE generation was around or above the power system load. Synchronous RE generator (SC and BES) was present in the system. Initially, with a DG present, BES was charged on surplus RE. When DG shut down around 1,100 seconds into the measurement, BES was managing variability of renewable power output and regulating system frequency. SC was providing system inertia while consuming about 100 kW to cover its losses. Fig. 3 (right) measurement demonstrates that a stable, steady-state operation of a megawatt – scale power system can be maintained for prolonged periods of time without diesel generation, but with a presence of a synchronous RE generator.

Finally, Fig. 4 presents high speed measurement (sampled at 1 kHz) of distribution faults during the renewable operation of the King Island IPS (no diesel generation). Around 60th second into the measurement, a fault occurred on one of King Island IPS's feeders which caused feeder protection to open the feeder circuit breaker. Five seconds later (around 65th second into the measurement), feeder reconnected but tripped again. Another five seconds later (around 70th second), feeder re-connected, but tripped once again about three seconds later. During this time, RE generation was covering most of the load, while the BES was supplying the difference. DGs were shut down during the entire measurement. This measurement presents that a megawatt-scale power system operating at high RE penetration levels can maintain power system stability during adverse power system events, without any diesel generation on-line, but with a presence of a synchronous RE generator.

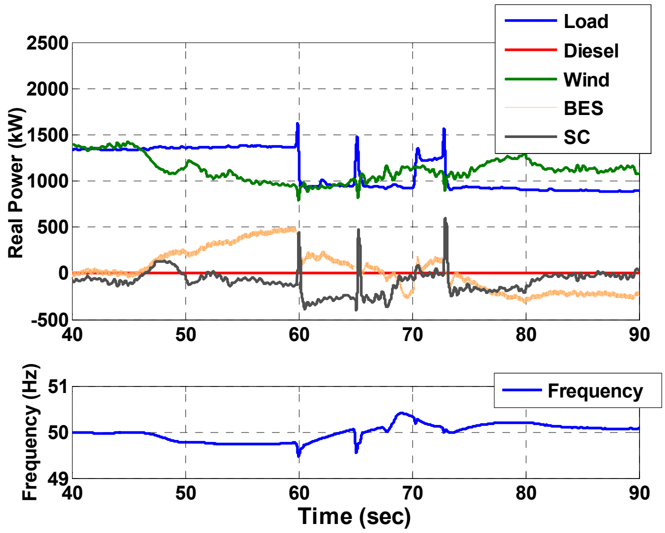

Fig. 4. Measurement data showing Synchronous Condensers (SC) responding to distribution faults

4. Discussion

In traditional IPSs, DGs are usually the main source of electric energy and they regulate the system frequency and voltage. They are also the main source of system inertia. Most of the DG inertia is stored in its alternator [12], or the synchronous machine part of the genset, while rotating parts of diesel engine contribute to the genset inertia with much less. Hence, most of a DG inertia could be mimicked by the inertia of a synchronous condenser.

DGs are devices capable of providing all services a power system needs; however, this comes with an ecological price. In contrast, synchronous RE generator (BES and SC) can provide all the services DG provides.

To further present technical statements from Section II, this paper presented real-world measurement taken from our case study system. Measurements clearly demonstrate that synchronous RE generators:

- Could bring inertia to a power system comparable (or even higher) to inertia which is provided by traditional DGs,
- Can maintain power system stability, frequency and voltage with no DGs present, and
- Can supply fault currents necessary for clearing of distribution faults, without the need for DGs.

In addition to technical comparisons with traditional DGs, the cost of energy from a synchronous RE generator is comparable to a price from a DG, but without GHG emissions.

Negative sides of a synchronous RE generator were mentioned as higher complexity than DGs; they would require higher skilled staff and larger installation space. Synchronous RE generator does not generate electric energy but uses some of the power generated elsewhere to cover its operational losses. This is why this technology is best used in high

RE penetration systems which experience high RE surplus. In conclusion, synchronous RE generator is an environmentally friendly technology which enables IPSs to operate at very high or entirely RE penetration levels, while enjoying the power system stability once provided by conventional DGs.

5. Conclusion

With the power industry being one of the major contributors to global warming, a sense of urgency is imposed on policy makers and power system operators to accept further RE generation. Enabling technologies which mitigate negative effects from RE generators are showing mixed techno-economic results. One of the prime enabling technology candidates, battery energy storage technology promises a lot, but is still in development, and cannot fully supplement RE generation in power systems.

This paper presented a concept for an enabling technology which leverages both positive sides of battery energy storage and synchronous generation in a synergy of a synchronous condenser and a battery energy storage, dubbed Synchronous RE generator. This technology was proven through a multi-year operation in an IPS of King Island in Australia, and the paper presented measurements which were recorded by power stations data logging equipment during a normal power system operation. Measurements prove that a Synchronous RE generator is capable of substituting diesel generation in an isolated power system, while supporting 100% instantaneous renewable energy penetration. Additionally, we have presented measurements which prove that this technology provided sufficient support during distribution system faults and helped the rest of the power system to ride through it.

In this paper, authors have presented an enabling technology concept based primarily on conventional technologies and demonstrated its merits through presented real-world measurements. As the technology is easily replicable, authors see its immediate application and its benefits to high renewable penetration isolated power systems around the world.

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