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Rapid synchronisation of fast instantaneous reserves CAES generator

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ABSTRACT

Electric power systems maintain system security by keeping instantaneous reserves that can substitute for a credible loss of generation. Instantaneous reserves are fast responding generators that maintain electric power system frequency immediately following a sudden mismatch between generation and load, and these are an indispensable system security tool. These are typically offered by partially or unloaded generators which are already synchronised to the AC network. The reserve requirement constrains generator operation, and reduces system flexibility and efficiency. These are important issues in a renewables-based power system. A compressed air energy storage and hydraulic actuation system is proposed to provide instantaneous reserves without constraining existing generators. By rapidly accelerating and synchronising a generator to the AC grid through a pressurised hydraulic drive, the cost of running unloaded or under-loaded spinning generators can be eliminated. This paper presents a novel hydraulic actuation system which is capable of achieving simultaneous frequency and phase matching between the power system and a 100 kW generator within 1 s. The hydraulic drive system, instrumentation, and the nonlinear controller design are described. In simulations, successful synchronisation is achieved under a wide range of system uncertainties.

1. Introduction

Electric power system contingent events describe a loss of generation resulting in a fall of AC frequency which can be economically managed by generation resources. These frequency swings are often caused by a loss of transmission or generation assets. To compensate for a shortage of generation, reserves are required to maintain frequency support. These are sometimes separated into fast instantaneous reserves (FIR) to alleviate short term frequency decay, and sustained instantaneous reserves (SIR) for longer term frequency support [1]. FIR and SIR are typically provided by grid synchronised generators running either partially loaded or unloaded. The ability of a generator to contribute to SIR is strongly dependent on the type of generation, and the speed of its governor response. Reserve generation may not be running at the most efficient operating point, and the reserve requirement constrains generator output.

Compressed Air Energy Storage (CAES) systems were first introduced in the 1970s to help meet peak loads. The concept required significant compressed air storage volumes, typically relying on underground caverns. A large CAES system was built in Huntorf, Germany, in 1978 [2], with a capacity of 290 MW, and a second in McIntosh, Alabama in 1991, with a capacity of 110 MW [3]. Each of these systems could run for a number of hours, and were expected to operate on a daily basis.

There is a compelling argument to use CAES systems for reserve requirements. Reserves are expensive - they require rotating machinery with the ability to generate more at short notice. This requires either unloaded or partially loaded rotating plant, which constrains dispatched generation and increases system losses. The existence of reserve markets is evidence of the monetary worth of reserves. As reserves are typically only required for a short time until other forms of generation can be brought online, the amount of energy storage required is relatively small, and the accumulator can use commonly available industrial compressed air piping. A CAES reserves system has no standing losses, and removes this constraint from other more active generation sources. The only cost is capital, which is minimised when off-the-shelf accumulators (compressed air pipework) and hydraulic components are used. Although CAES systems are not very efficient, if they are only used during contingent events the efficiency is of minimal importance. The key limitation is the ability to rapidly transfer the stored energy into electrical power injected into the electric power system.

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In this paper a CAES system is proposed to store energy and use it for instantaneous reserves. The efficient operation of the system depends on the generator remaining at stand-still until a contingent event. The system is designed to accelerate a generator to synchronism and connect to the electric power system, achieving full power output within a short time.

A synchronous generator can only be synchronised to a power system when the instantaneous phase and frequency are closely matched. Generator connection that is performed with considerable differences in phase or frequency can result in damage due to mechanical stress, false tripping of protection relay elements from inrush current, initiation of voltage oscillations, and disturbance to nearby equipment [4]. Traditionally the synchronisation procedure is carried out by an auto-synchroniser, which is a speed regulating system that drives the generator at a speed close to, but not exactly, the AC network frequency. Instead of actively controlling generator phase angle to match the EPS phase angle, the angular error is gradually decreased through the small difference frequency.

Normally, time is not constrained for auto-synchronisers, and the synchronisation process can take minutes. The proposed CAES system aims to achieve generator acceleration and synchronisation within 1 s from stand-still. This paper presents the proposed system, and a novel rapid auto-synchronisation scheme capable of achieving rapid synchronisation regardless of initial generator and power system conditions. The intent of the paper is to show that with existing hydraulic and generator technology, rapid acceleration and synchronisation is possible. Proof of concept hardware is currently being built.

2. System overview

Fig. 1 shows the simplified CAES system hydraulic circuit. By compressing the gas charged accumulator through a electric hydraulic fluid pump, energy is stored in the form of compressed gas, which is then released via a proportional throttle valve (PTV) to drive a hydraulic motor. The hydraulic motor drives a 4 pole synchronous generator. The effectiveness of such a system depends on the characteristics of and performance of the system components. For this proof of concept prototype, a 100 kW system is proposed. The main components and their key properties are discussed below: The accumulator is pre-charged to 250 bar.

The PTV is a Parker TDA NG16. This uses an electrical solenoid to control a soft-shift spool, smoothly varying its orifice area to control the fluid velocity/pressure drop relationship across the valve. This in turn controls the pressure across the hydraulic motor, controlling the torque.

The hydraulic motor is a variable displacement Parker gold cup M14 machine. The variable displacement means that generator torque can be maintained as the accumulator pressure slowly drops. However, during the start-up and synchronisation phase, the displacement is fixed, and control is implemented via the PTV.

The generator is an ABB 100kVA AMG0250AA04 four pole synchronous machine. Its rated speed is 1500 rpm, and at this speed the mechanical torque for 100 kW is 640 Nm. The rotor inertia is 1.46 kgm^2, so during the acceleration phase, rated torque can achieve synchronous speed in less than 0.4 s.

3. Synchronisation control

Spinning the generator up to synchronous speed, achieving phase angle synchronisation in less than one second is a significant challenge. There are some criteria that need to be met before the generator can be connected to the power supply grid. The standard synchronisation limit recommendation for a distributed generator given by IEEE [5] and ABB [6] is shown in Table 1:

The synchronisation criteria in this paper are to achieve phase and frequency matching to 15° and 0.3 Hz before connection to the electric power grid.

3.1. Reference input synthesis

The dynamic performance of the overall system is limited by the dynamics of the hydraulic proportional throttle valve (PTV). Attempting fast control according to the traditional synchronisation strategy means setting a target speed, and waiting for or controlling for phase synchronisation. Setting a target speed requires considerable valve operation - from nearly fully open for maximum acceleration, to nearly fully closed while unloaded speed is maintained until synchronisation is achieved, and nearly fully open again for full power transmission to the electric power grid.

For this application a strategy has been designed that minimises the dynamic requirements of the PTV, while optimising speed of synchronisation and smoothing the transition to full power generation. The synchronisation controller synthesises a constant generator target acceleration α_g which results in the generator's mechanical frequency (ω_g) and phase angle (θ_g) matching that of the power system frequency (ω_s) and phase angle (θ_s) simultaneously at some time T. For this to work, a particular cycle of the

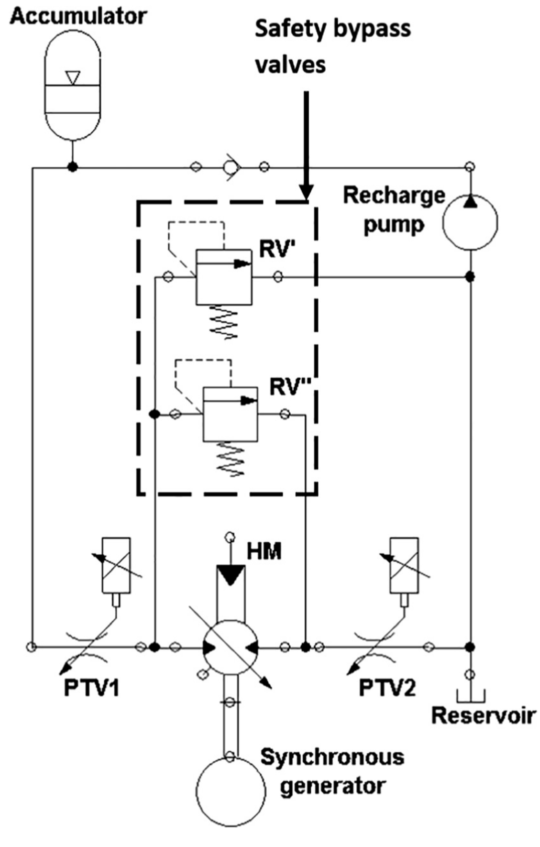

Fig. 1. Simplified CGES hydraulic circuit diagram.

Table 1
Recommended synchronization limits.

Parameters	IEEE Standard	ABB Manual
Phase angle	20°	15°
Frequency	0.3 Hz	0.7% (0.35 Hz)
Voltage	10% (40 V)	2% (2 V)