The impact of Variable Renewable Energy (VRE) on the power system stability – The renaissance of synchronous condensers

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Abstract

The energy transition, i.e. the strategic change from fossil fuels to renewable energy sources, entails a fundamental transformation of the transmission and distribution grids. The electric power system is in transition which shifts from a rotating mass-dominated system to a power converter-dominated system. Without the appropriate measures, this will have a negative impact on power system stability. This report describes the implications of the transformation of the electric power system on voltage stability and frequency stability, it compares Synchronous Condensers (SynCon), SVCs (static VAR compensation) and static synchronous compensators (STATCOM) with regard to the different grid needs. SynCons, which have been used for reactive power compensation since the early 20th century, and have been replaced by other technologies in the meantime, are experiencing a renaissance in transmission and distribution grids [1].

German abstract

Die Energiewende – strategischer Übergang von fossilen Brennstoffen hin zu erneuerbaren Energiequellen – bringt einen fundamentalen Umbau der Übertragungs- und Verteilnetze mit sich. Das elektrische Energiesystem befindet sich im Übergang eines schwungmassendominierten Systems in ein stromrichterdominiertes System. Dies hat, ohne entsprechende Maßnahmen, negative Auswirkungen auf die Netzstabilität zur Folge. Dieser Bericht beschreibt die Auswirkungen der Transformation des elektrischen Energiesystems auf die Spannungs-stabilität und die Frequenzstabilität, es werden die unterschiedlichen Kompensationsanlagen im Hinblick auf die unterschiedlichen Kompensations-anforderungen verglichen. Rotierende Phasen-schieberanlagen (RPSA), welche seit Anfang des 20. Jahrhunderts zur Blindleistungskompensation eingesetzt wurden und zwischenzeitlich durch andere Technologien ersetzt wurden, erleben eine Renaissance in Übertragungs- und Verteilnetzen [1].

Keywords

Synchronous condenser, instantaneous reserve (or inertial response), inertia, kinetic energy, rotating mass, short circuit power, short circuit contribution, reactive power compensation, power system stability, frequency stability, voltage stability

Synchronous generation units and variable renewable energy

As the share of renewable energy sources in power generation increases, fossil fuel sources are being phased-out - good for the climate, albeit a huge challenge for transmission grids. Over the past 20 years, the global share of renewable energy in annual new generation plant additions has increased from 15% in 2002 to 83% in 2022 [2]. This growth is primarily driven by photovoltaics and wind power. In 2020, these renewable forms of energy had a global generation capacity share of 19%; by 2050, this share will increase to 67%, provided that the energy transition measures planned to date are taken into account [2]. Photovoltaic and wind power have in common that their instantaneous generation depends on the supply currently available (solar irradiation and wind, respectively). These forms of energy are therefore referred to as Variable Renewable Energy (VRE).

To meet the Paris targets of no more than 1.5°C global warming, the share of variable renewable energy in total generation capacity must increase to 81% by 2050 [2].

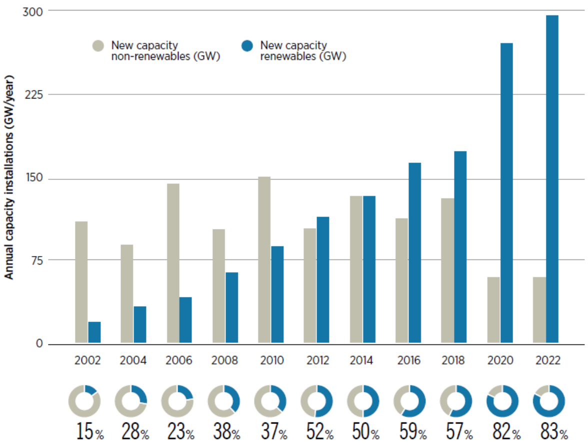


Figure 1: Expansion of new generation plants according to [2].

As soon as renewable energy sources feed into the grid, they supersede conventional thermal power plants, given that renewable energy enjoys feed-in priority in most countries due to regulatory framework conditions (merit order). This results in a power generation transition from a rotating mass system to a inverter based resources (IBR) system. In other words, the rotating mass in the electrical power system decreases to the same extent as the proportion of wind and solar power generation increases, which is coupled via inverters.

HVDCs (high-voltage direct current transmissions), which are used to transmit large power outputs over long distances, and the connection of battery storage systems to the three-phase transmission grid, also take place using inverters.

Another challenge is that large variable renewable generation plants are, in many cases, located far away from the consumption centers on the grid (e.g. offshore wind), which is why it is more common for large outputs to have to be transported over long distances. This is no longer in line with the structure and operation of the synchronous grid of Continental Europe. According to [3], the Frequency Containment Reserve, also known as primary control reserve, is dimensioned to be able to intercept a fault with a total power of +/-3 GW in the synchronous grid of Continental Europe. However, since the primary control responds with a delay, sufficient instantaneous reserve is required to keep the rate of change of frequency (RoCoF) as low as possible to ride through frequency events without any harm to the rest of the power system.

High penetration of the grid with inverter-coupled (generation) equipment leads to lower stability of the electric power system, namely reduced frequency stability, reduced voltage stability, reduced rotor displacement angle stability, reduced resonance stability and reduced inverter-based stability.

Grid-connected inverter-coupled generation equipment does not provide instantaneous reserve, so-called inertia, which is inherently provided by the rotating masses of the synchronous generators. Inverter-coupled generation equipment also provides no, or very little, short-circuit power. Both of these factors reduce power system stability. Possible consequences include wide-scale, undamped voltage and power oscillations, degradation of generator performance during faults, malfunctions or failures of protective equipment, Fault Induced Delayed Voltage Recovery (FIDVR) [4], [5], greater voltage jumps after capacitor banks are connected or disconnected, increased harmonic harmonics, deeper voltage dips, and higher voltage transients. Then again, due to higher frequency gradients, i.e. RoCoF (rate of change of frequency), increased frequency instability occurs, which leads to a deterioration of the system protection fault detection. All of this results in limited power system hosting capacity for new renewable wind and photovoltaic units.

Historically, system strength (grid resilience) [6] and system inertia were not the main focus because they were available in abundance as the result of the high proportion of synchronous generators on the grid. Grid compensation systems therefore had one main function, which was to provide and absorb reactive power. Originally, SynCons were used for this task as from the early 20th century. Since the 1980s, there have been hardly any new SynCons. Existing systems were refurbished or replaced by static reactive power compensation (SVCs , STATCOMs), since these newer technologies could offer pure reactive power compensation at lower cost. However, with the ever-increasing share of converter-coupled generation equipment, the requirement for compensation systems changed considerably. Compensation systems should now also provide instantaneous reserve (inertia) and short-circuit power. Due to the fact that existing SVCs and STATCOMs cannot provide both, the SynCon is experiencing a remarkable renaissance, since the world market for SynCons is growing rapidly!

Power system stability

Power system stability refers to the ability of an electric power system, under given initial operating conditions, to return to a state of operating equilibrium after a physical fault, limiting most system variables to keep virtually the entire system intact.

Power system stability is determined by the physical configuration and features of the power system. The physical configuration is determined by the topology of the power grid, the technology mix of the generation plants, the power plant fleet currently feeding into the grid, the consumer types on the grid, the percentage of renewable energy generators connected to the distribution grid, current load and local distribution of the load, settings and coordination of protection systems, and the control system. The features are determined by current active and reactive power flows, the extent of available balancing power, the extent of available reactive power compensation capacity, dynamic load behavior, instantaneous reserve (inertia), generator synchronization torque, damping torque, coordination of protection systems, and system strength.

Figure 2 shows the five categories of power system stability [7]; these are voltage stability, frequency stability, rotor displacement angle stability, resonance stability, and inverter-based stability. The latter two were only added in 2020 due to the ever-increasing share of inverter-coupled renewable generation equipment [7].

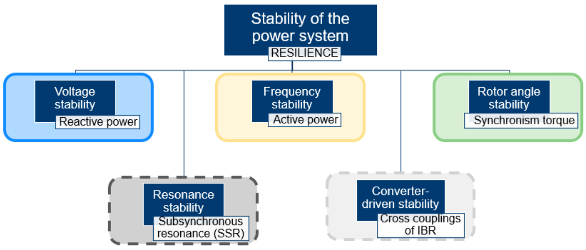


Figure 2: Categorization of power system stability according to [7]:

Voltage stability

Voltage stability is specified by the system strength of the power system. It can be generally described as the ability of the power system to maintain and control the pure sinusoidal shape of the voltage at any location in the power system, both during steady-state operation and after a fault. Three-phase short circuit power is used to specify the minimum system strength requirements at affected power system points. The short-circuit power is proportional to the rated voltage and the short-circuit current.

In voltage stability, a distinction is made between steady-state voltage support and transient stability. For steady-state voltage support, conventional reactive power compensation devices are used, such as mechanically switched capacitors (MSCDN, Mechanically Switched Capacitor with Damping Network), static VAR compensation (SVC; by means of semiconductors switched capacitors or chokes), STATCOM, but recently also more frequently SynCons.

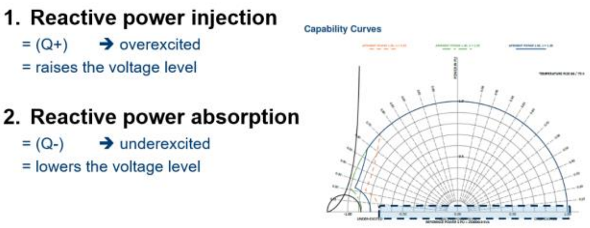


Figure 3: Steady-state voltage support - overexcited and underexcited operation of the SynCon

Transient stability is determined by the amount of short-circuit power. SVCs and STATCOMs can provide only a minimal contribution here because of their limited overload capability. In contrast, typical SynCons can deliver up to five times the rated apparent short circuit power. For example, a SynCon with a rated apparent power of 250 MVA delivers approximately 1250 MVA of short circuit power (the so-called short circuit contribution; SCC).

The short circuit contribution of the total system of a SynCon is calculated using formula (1). The subtransient longitudinal reactance of the SynCon and the reactance of the machine transformer are the main parameters that determine the magnitude of the short circuit contribution. Unlike conventional power plants, where the short circuit contribution may be sought to be limited by increasing the reactance of the machine transformer, SynCons deliberately use a transformer with the lowest possible reactance (u_k of 10% or less).

$$SCC = \frac{S_{SC}}{\left(x_d'' + \frac{S_{SC}}{S_T} u_k\right)} \tag{1}$$

In this relation, SCC is the short circuit contribution in MVA, S_{SC} is the rated apparent power of the SynCon in MVA, S_T is the rated apparent power of the machine transformer, x_d'' is the subtransient longitudinal reactance of the SynCon in p.u., and u_k is the short circuit voltage of the machine transformer in p.u. .

Frequency stability

One characteristic of a high-quality power supply is a grid frequency that is as constant as possible (e.g. 50 Hz in the European interconnected system). Imbalances between power generation and consumption cannot, in principle, be avoided and are manifested by a change in the grid frequency.

Basically, the instantaneous reserve (inertia) on the grid and the amount of available primary control power are responsible for the frequency stability. The instantaneous reserve is subject to daily (see example in Figure 4) or seasonal (Figure 5) fluctuations due to the generation mix. In the synchronous grid of Nordic Power System, the instantaneous reserve is therefore monitored in real time to ensure that sufficient rotating mass is available at all times.

Period: 1.8.2023 - 7.8.2023

Voit tarkastella arvoja tarkemmin rullaamalla hiirtä kuvaajan päällä

	Name	Minimum	Maximum	Average
●	Inertia	142	202	173 GWs

Figure 4: Instantaneous reserve in the Nordic Power System (Europe) - first week of August 2023 [8]

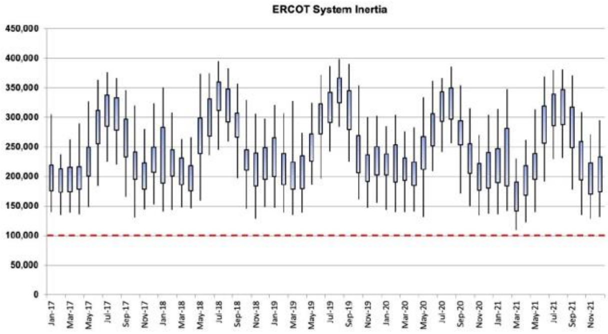
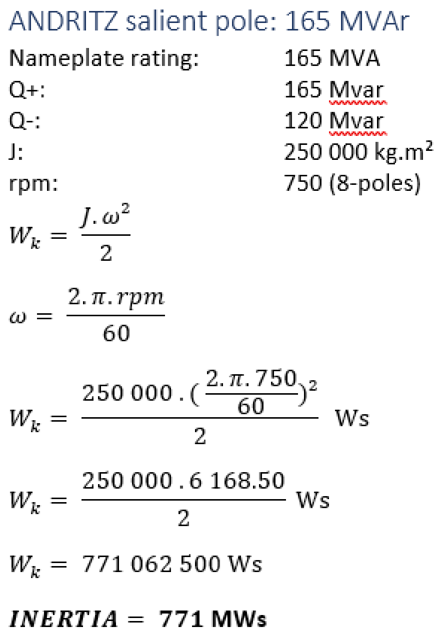


Figure 5: Instantaneous reserve in the ERCOT interconnection (Texas, USA) - 2017 to 2021 [9]

The instantaneous reserve in the synchronous grid is determined by the sum of all synchronous machines connected to the grid, this includes synchronous generators as well as synchronous motors. Since the number of synchronous motors connected to the grid cannot be determined, or is very difficult to determine, in practice only the sum of the kinetic energy of the synchronous generators plus SynCons is used to determine the instantaneous reserve. The kinetic energy of a rotating unit W_k is calculated according to equation (2).

$$W_k = \frac{J.\omega^2}{2} \tag{2}$$

In this relation, J is the mass moment of inertia in kg m² and ω the angular velocity of the rotor in rad^{-1}. The mass moment of inertia (also called moment of inertia; formerly not SI-conform GD² "moment of inertia") is determined by the geometric shape and the weight of the rotor. Greater weight and higher diameter increase the rotor's mass moment of inertia. This is considerably higher for a salient-pole machine than for a cylindrical-rotor machine. The nominal speed (lower for salient-pole machines) is also included in the kinetic energy calculation, but the mass moment of inertia is the determining factor. In practice, the inertia (kinetic energy) of a salient-pole machine is more than twice that of a comparable cylindrical-rotor (see Figures 6a and 6b).



ANDRITZ salient pole: 165 MVAr

Nameplate rating: 165 MVA
Q+: 165 Mvar
Q-: 120 Mvar
J: 250 000 kg.m²
rpm: 750 (8-poles)

$$W_k = \frac{J.\omega^2}{2}$$

$$\omega = \frac{2.\pi.rpm}{60}$$

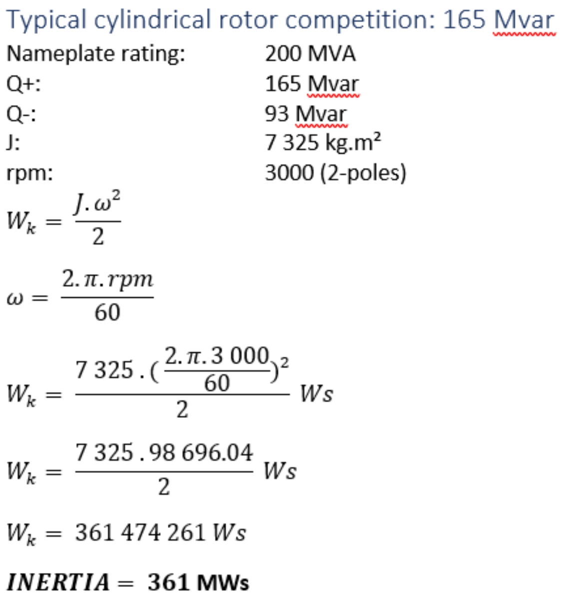
$$W_k = \frac{250\,000\,.\,(\frac{2.\pi.750}{60})^2}{2}\ \text{Ws}$$

$$W_k = \frac{250\,000\,.\,6\,168.50}{2}\ \text{Ws}$$

$$W_k = 771\,062\,500\ \text{Ws}$$

$$\boldsymbol{INERTIA} = \textbf{771 MWs}$$

Figure 6a: Calculation of kinetic energy 165 Mvar salient-pole machine



Typical cylindrical rotor competition: 165 Mvar

Nameplate rating:	200 MVA
Q+:	165 Mvar
Q-:	93 Mvar
J:	7 325 kg.m²
rpm:	3000 (2-poles)

$$W_k = \frac{J.\omega^2}{2}$$

$$\omega = \frac{2.\pi.rpm}{60}$$

$$W_k = \frac{7\,325\,.\,(\frac{2.\pi.3\,000}{60})^2}{2}\ Ws$$

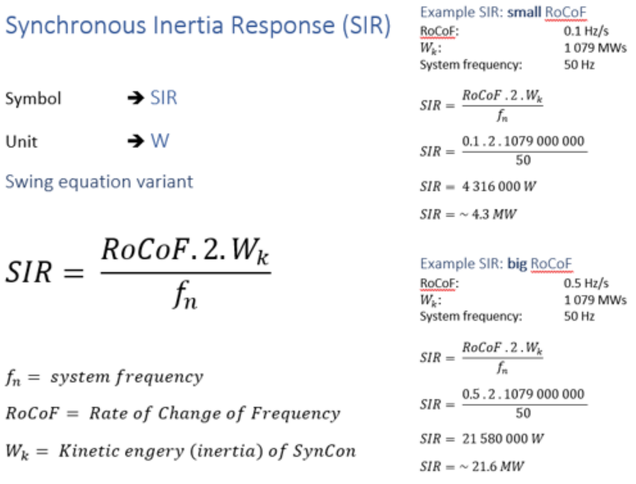
$$W_k = \frac{7\,325\,.\,98\,696.04}{2}\ Ws$$

$$W_k = 361\,474\,261\ Ws$$

$$INERTIA = \textbf{361 MWs}$$

Figure 6b: Calculation of kinetic energy 165 Mvar cylindrical-rotor machine

The amount of instantaneous reserve in MW, which is injected into the grid after a frequency jump, to support the frequency depends on the size of the frequency jump. See the example of a SynCon of the salient-pole machine type with a nominal apparent power of 250 Mvar and an inertia of 1079 MWs in Figure 7.



Synchronous Inertia Response (SIR)

Symbol ➔ SIR

Unit ➔ W

Swing equation variant

$$SIR = \frac{RoCoF.2.W_k}{f_n}$$

$f_n =$ system frequency

$RoCoF =$ Rate of Change of Frequency

$W_k =$ Kinetic engery (inertia) of SynCon

Example SIR: **small** RoCoF

RoCoF:	0.1 Hz/s
W_k:	1 079 MWs
System frequency:	50 Hz

$$SIR = \frac{RoCoF\,.\,2\,.\,W_k}{f_n}$$

$$SIR = \frac{0.1\,.\,2\,.\,1079\,000\,000}{50}$$

$$SIR = 4\,316\,000\ W$$

$$SIR = \sim 4.3\ MW$$

Example SIR: **big** RoCoF

RoCoF:	0.5 Hz/s
W_k:	1 079 MWs
System frequency:	50 Hz

$$SIR = \frac{RoCoF\,.\,2\,.\,W_k}{f_n}$$

$$SIR = \frac{0.5\,.\,2\,.\,1079\,000\,000}{50}$$

$$SIR = 21\,580\,000\ W$$

$$SIR = \sim 21.6\ MW$$

Figure 7: Amount of fed instantaneous reserve at different frequency gradients

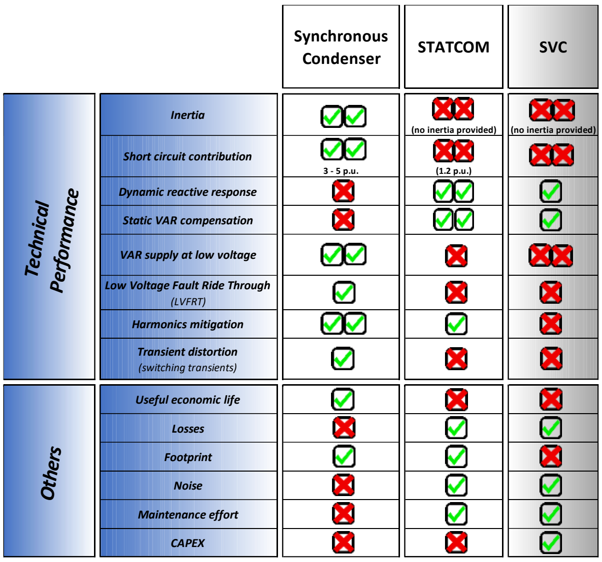
At a frequency gradient of 0.1 Hz/s, this SynCon responds with an instantaneous power jump of approx. 4.3 MW; at a frequency gradient of 0.5 Hz/s, it even responds with an instantaneous power jump of approx. 21.6 MW.

Main functions of synchronous condensers

Synchronous condensers are extremely grid-serving systems whose main functions are:

1. **Improvement in frequency stability**
2. **Improvement in transient stability**
3. **Improvement in steady-state voltage support**

Frequency stability and transient stability are necessary whenever faults occur in the synchronous grid. These can be large load sheddings or the failure of a large power plant in the case of faults in the grid frequency, or short circuits in the case of transient voltage stability. SVCs and STATCOMs do little, or nothing, to improve either of these stabilities.



		Synchronous Condenser	STATCOM	SVC
Technical Performance	***Inertia***	☑☑	☒☒ (no inertia provided)	☒☒ (no inertia provided)
	Short circuit contribution	☑☑ 3 - 5 p.u.	☒☒ (1.2 p.u.)	☒☒
	Dynamic reactive response	☒	☑☑	☑
	Static VAR compensation	☒	☑☑	☑
	VAR supply at low voltage	☑☑	☒	☒☒
	Low Voltage Fault Ride Through *(LVFRT)*	☑	☒	☒
	Harmonics mitigation	☑☑	☑	☒
	Transient distortion *(switching transients)*	☑	☒	☒
Others	***Useful economic life***	☑	☒	☒
	Losses	☒	☑	☑
	Footprint	☑	☑	☒
	Noise	☒	☑	☑
	Maintenance effort	☒	☑	☑
	CAPEX	☒	☒	☑

Figure 8: Aspects of different technologies

Figure 8 compares various aspects of different technologies for reactive power compensation.

Summary and outlook

Instantaneous reserve and short-circuit power are essential system services, which are available during high penetration of wind and, to a lesser extent, photovoltaic systems. Previously common compensation devices cannot supply both. SynCons are therefore continuously gaining in importance.

In practice, the following trend can be observed: Static VAR compensation (SVCs) is being replaced by STATCOMs due to functional advantages when it comes to pure reactive power compensation and thus steady-state voltage support. SynCons are increasingly being used when compensation systems are put out to tender that go beyond pure reactive power compensation. New forms of STATCOM are being developed, so-called E-STATCOMs, which will provide virtual inertia in the future due to their grid-forming function, but these will not be able to replace SynCons, because of SynCons ability to provide the services concurrently. Virtual inertia is understood as the ability to absorb or release active power without delay during frequency changes, even without rotating mass, which requires an appropriately dimensioned electrical energy storage.

The different types of compensation systems should be considered complementary, since, as Figure 8 shows, they all have their type-specific advantages and disadvantages. Grids in the future will therefore be compensated by a mixture of SynCons, STATCOMs / SVCs and MSCDN.

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