A new method for integrating and controlling synchronous generators in power systems

Description

For several decades, the well-known dynamics of SGs dominated the power systems operation and control. The operation of SGs with power systems can be visualised by two conveyer belts that are connected by a chain (with no slip), which means they will run at the same speed. In other words, the rotor speed of the SGs (mechanical frequency) is proportional to the electrical frequency (1/one-cycle-time), hence it is called “synchronous” generator. Due to the electromechanical coupling between the SGs and the power systems, any disturbance on the power system (e.g. short circuits or sudden changes of generation/load) will be reflected on the SG (as a mechanical torque). The inertial capacity of the SG will, therefore, naturally helps suppressing the oscillations caused by the disturbance.

Distributed energy resources (DERs) are decoupled from the network through power electronic converters (PECs), that perform power conditioning, e.g. maximum power point tracking (MPPT). Currently, most PECs are controlled in “grid-following” mode, where the grid imposes the voltage and frequency and the DERs feed a certain amount of power into the network. Therefore, DERs do not contribute to the system inertia even if they have a rotating mass. Hence, as the penetration of PEC-based units increases, there is a correlated reduction in the system inertia, increasing the risk of instability. A plethora of control algorithms have been proposed in the literature to alleviate the reduction in inertia. Although different names such as the virtual synchronous machine (VSM) or synthetic/virtual inertia are coined, the common idea is to make the DERs behave like SGs through making their interfacing PECs mimic the dynamics of an SG. Using synchronous condenser (SC)-based solutions to mitigate the inertia drop is also proposed.

In addition to the inertia reduction, high penetrations of DERs causes the following challenges for the network operators:

Short Circuit Level (SCL): while SGs supply a fault current of 5-7 pu, fault current contribution of a PEC is normally about 1.1-1.2 pu. This difference between the SCL contribution may disrupt the operation of the overcurrent protection systems since the fault level will change with different operating conditions. For example, in a day with a high penetration of DERs the overcurrent relays, because of their inverse time characteristics, may operate with much longer delay or may not even operate.

Transient phase angle change: in SGs the rotor angle is also the phase angle between the excitation voltage and the terminal voltage. Since rotor angle cannot change quickly, sudden changes of voltage phase angle can trip SGs. The issue becomes more problematic during re-connecting two parts of the system, where care must be taken to make sure that the two sections are fully in phase.

Rate of Change of Frequency (RoCoF): As inertia drops, RoCoF increases. Therefore, a generation/load loss may lead to the RoCoF exceeding the settings of RoCoF-based protection, which would result in unnecessary loss of DERs, and can lead to further disturbances.

While contributing a short circuit current of more than 5 pu is not an issue for SC-based solutions, the only way to do so for a PEC-based (VSM-controlled DERs) solution is to choose over-sized switches (it is also possible to de-load the DERs during normal operation to have enough capacity available for SCL contribution. This approach will, of course, not be appealing to the DERs' owners). Using SCs in effect means substituting SGs with almost the same infrastructure, which can increase the energy price. Moreover, SCs are likely to be fossil-fueled, which undermines integrating more renewable energy in the first place. Using a PEC with over-sized switches (assuming technically possible for high powers) appears to be an over-engineered solution that also increases the price.

On the other hand, while voltage angle deviation ride-through requirements are not an issue for VSM-based solutions (since PECs can withstand large phase differences), they can be problematic for SC-based solutions (as SC is basically a synchronous machine).

It is noted that the RoCoF-based protection for DERs is an islanding detection method, which can, theoretically, be further relaxed (as GB National Grid already did) or even removed. However, since in the current network structure, frequency has both electrical (1/one-cycle-time) and mechanical/physical (rotor speed of SGs) meanings, RoCoF depends on the rate of change of the rotor speed. Because of this dependency between the mechanical and electrical frequency, further relaxation of RoCoF (and frequency nadir) regulations may endanger SGs operation.

In light of the above complications, unlike the popular approach that tries to make the DERs behave like a SG, this patent proposes to decouple all SGs from the network using fully-controlled back-to-back AC/DC/AC PECs as shown in Figure 1. The network-side converter (NSC), which is controlled using the algorithm shown in Figure 2, determines the SG power (P_{sg}) through the virtual automatic voltage regulator (AVR) and the rotor speed limiting mechanism. The SG power (P_{sg}) is then imposed on the SG by the generator-side converter (GSC) through controlling the DC-link voltage (V_{DC}) by regulating the SG's active current ($I_{ac\text{-}sg}$).

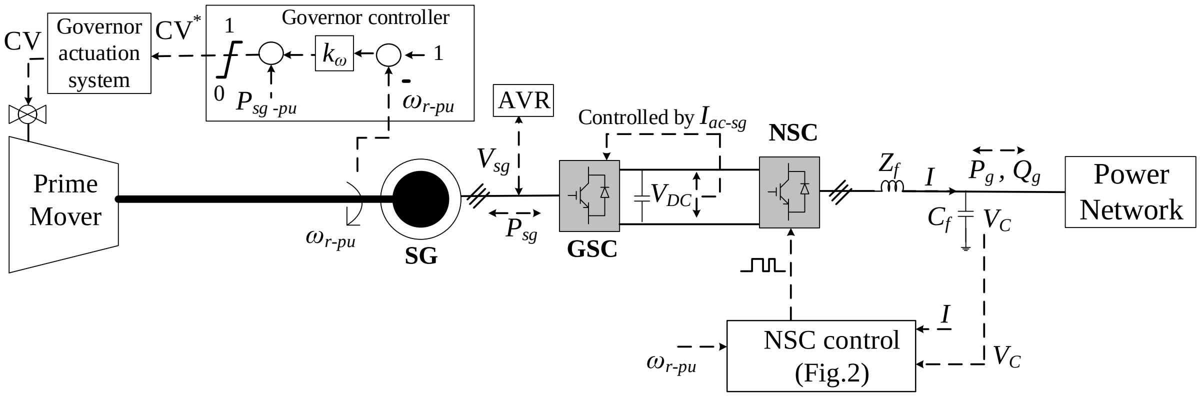

Figure 1. SG augmented by the fully-controlled back-to-back AC/DC/AC converters

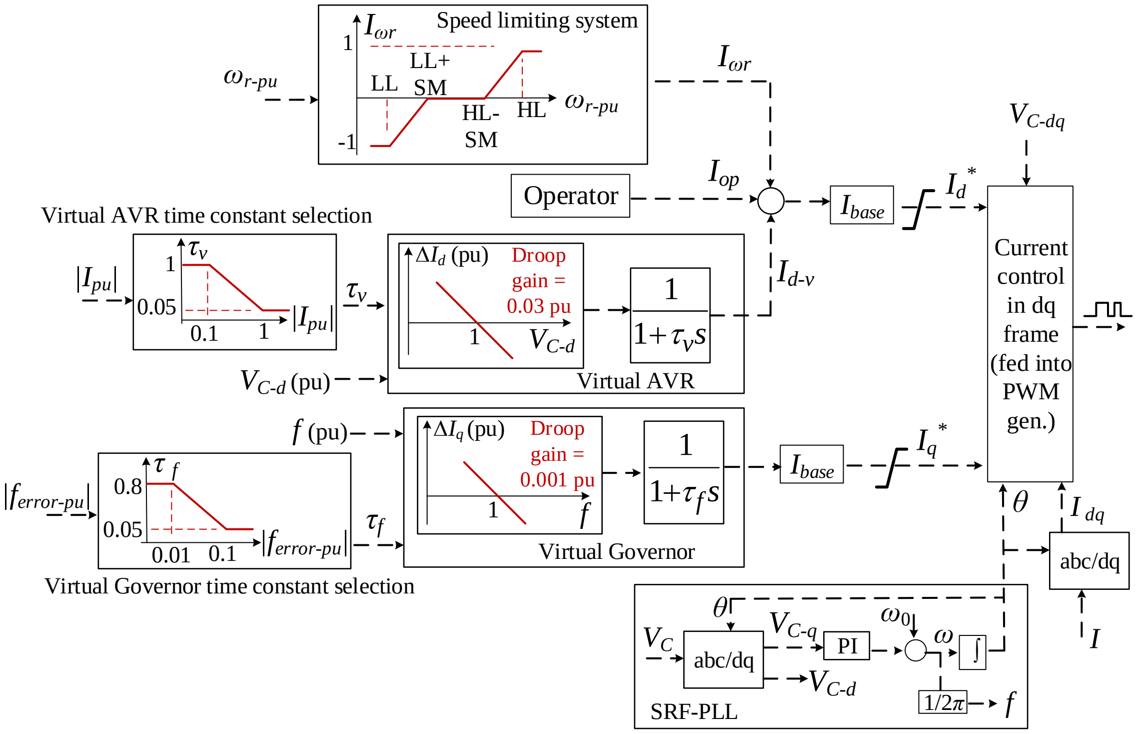

Figure 2. Control structure of the network-side converter (NSC) of the SG.

The Governor controller shown in Figure 1 is proposed to control the SG's prime mover. The reference control valve (CV^*) is set by the Governor controller, which is fed to the actuation mechanism to regulate the mechanical input power from the prime mover (e.g. a steam turbine). The control valve (CV) can vary from fully closed (i.e. 0) to fully open (i.e. 1). This value, at steady state, is equal to the per unit (pu) value of the SG's power $P_{sg\text{-}pu}$ (neglecting losses). A proportional controller (k_ω) is used to maintain the rotor speed ω_r transient response. A PI controller is not used as it is no longer needed to keep ω_r at 1 pu (i.e. 50 Hz) at steady state, which enhances the energy storage (ES) capability of the SG.

Both the GSC and the NSC are current-controlled in dq-frame. The active current component of the GSC ($I_{ac\text{-}sg}$) determines the SG's power (P_{sg}) by controlling the DC-link voltage (V_{DC}) using standard cascaded voltage and current loops. The reactive current component of the GSC is set to zero here, however, it can be used instead of (or alongside) the SG's AVR to control the SG's voltage (V_{sg}).

The control of the NSC, which is detailed in Figure.2, comprises a PLL, and the dq-channels as detailed below:

- The PLL sets the nominal frequency ω_0 and synchronizes the NSC through making $V_{C\text{-}q}=0$.

- The q-component reference current (I_q^*) is set through the virtual governor (I_{base} is the NSC's base current). The low-pass filter (LPF) time constant τ_f is dynamically sets according to the absolute value of the frequency error $|f_{error}|$. Using the proposed methods, as $|f_{error}|$ increases, τ_f drops to reduce the response time, while for small $|f_{error}|$ (at steady state), higher τ_f provides more damping.

- The d-component reference current (I_d^*) consists of 3 sub-components (all in per unit):

  - The operation current (I_{op}), which is set by the system operator according to technical and economical constrains.

- $I_{d\text{-}v}$, which is set by the virtual AVR according to the local voltage ($V_{C\text{-}d}$). The time - constate of the virtual AVR's LPF τ_v varies according to the magnitude of the NSC AC-side current |I|, which is imposed by the loads. Since at smaller loads oscillations increase, τ_v increases to increase damping. Reducing τ_v as current increases, also enables a fast and smooth black-start through establishing the voltage gradually.
- $I_{\omega r}$, which is set according to the rotor speed ω_r to maintain it between a high limit (HL) and a low limit (LL). Note that Since the proposed structure physically decouples the SGs from the network, the SGs' speed must no longer be 50 (or 60) Hz at steady state. The proposed control scheme exploits this situation to enable the SGs operating as ES mechanisms, meaning that their rotor speed can vary. However, there will be a practical limitation for the maximum/minimum limit of the rotor speed (e.g. due to the mechanical constrains). The HL and LL can be different for different types of SG. A safety margin (SM), e.g. 1-3%, is defined. For rotor speeds between LL+SM and HL-SM, $I_{\omega r}=0$. For rotor speeds between HL-SM and the HL, $I_{\omega r}$ varies between zero and 1pu, and for rotor speeds between LL+SM and the LL, $I_{\omega r}$ varies between zero and -1pu.

Advantages:

1- Using the proposed structure and control algorithm allows the full utilization of the inertial capacity of the SGs, despite the physical decoupling of SGs from the network.
2- Using the proposed structure and control algorithm enables further exploitation of a SG as an energy storage mechanism (since its rotor speed must no longer be kept at 50 (or 60) Hz).
3- Using the proposed structure and control algorithm protects the SG voltage (V_{sg}) from phase movement on the network.
4- Using the proposed structure and control algorithm for all SGs in the network;
    a. enables further relaxation (or even removal) of RoCoF-based protection as the electrical (network) frequency is separated from the mechanical frequency (SGs' rotor speed).
    b. makes the SCL contribution from all units (DERs and SGs) similar, which means that the overcurrent relays can be set accordingly.
    c. enables independent operation of each segment of the network.

Claims

1. A method of integrating the synchronous generators, used in fossil/nuclear/bio-fuelled power stations (here SGs), by connecting them to the network through fully-controlled back-to-back AC/DC/AC converters, and controlling the converters such that they impose power on the SG.
2. A method of integrating and controlling SGs according to claim 1, in which the Generator-side Converter (GSC) determines the SG’s power (P_{sg}) by controlling the DC-link voltage (between the NSC and GSC) through regulating the SG’s active current ($I_{ac\text{-}sg}$).
3. A method of integrating and controlling SGs according to claims 1 and 2, in which the SG’s Governor control system comprises a proportional controller (k_ω) that controls the SG’s rotor speed in per unit (pu) i.e. $(1-\omega_{r\text{-}pu})k_\omega$; which is added to the pu value of SG’s power ($P_{sg\text{-}pu}$); such that $P_{sg\text{-}pu}+(1-\omega_{r\text{-}pu})k_\omega$ is fed to the Governor actuation system.
4. A method of integrating and controlling SGs according to claims 1 to 3, in which the Network-side Converter (NSC), which connects the SG-GSC to a main electricity network, compromises:

    A phase-locked loop (PLL) that imposes nominal frequency (ω_0), measures local frequency (f), and provides phase angle (θ) for the Park and Invers-Park Transforms; and,

    A virtual Governor that controls the frequency through regulating the q-component of the NSC’s current I_q; and,

    A virtual automatic voltage regulator (AVR) that controls the AC-voltage through regulating part of the d-component of the NSC’s current $I_{d\text{-}v}$; and,

    A SG’s rotor speed limiting systems configured to maintain the rotor speed $\omega_{r\text{-}pu}$ within the allowed thresholds through regulating part of the d-component of the NSC’s current $I_{d\text{-}\omega}$; and’

    An input SG’s operating current (or power) set by the operator I_{op}.
5. A method of integrating and controlling SGs according to claim 4, in which the virtual Governor compromises the steps:

    An I_q-f droop (in pu) determines I_q according to the frequency (f) from the PLL, and feds I_q to a first order low-pass filter (LPF) with time constant of τ_f; and,

    The output of the LPF is multiplied by the NSC’s base current I_{base} to calculate the reference q-comment current I_q^*, which is fed to a standard current control loop in the dq-frame.
6. A method of integrating and controlling SGs according to claim 5, in which the time constant of the virtual Governor’s LPF (τ_f) is determined dynamically within a max/min threshold according to the absolute value of the frequency error $|f_{error\text{-}pu}|$.
7. A method of integrating and controlling SGs according to claim 4, in which the virtual AVR compromises the steps:

    An $I_{d\text{-}v}$-V_d droop (in pu) determines $I_{d\text{-}v}$ according to the d-component of the NSC’s AC voltage, and feds $I_{d\text{-}v}$ to a first order low-pass filter (LPF) with time constant of τ_v.
8. A method of integrating and controlling SGs according to claim 7, in which the time constant of the virtual AVR’s LPF (τ_v) is determined dynamically within a max/min threshold according to the absolute value of the magnitude of the NSC’s AC current $|I_{pu}|$.
9. A method of integrating and controlling SGs according to claim 4, in which the rotor speed limiting system compromises the steps:

    Setting $I_{d\text{-}\omega}$ equal to zero for rotor speeds between the low limit plus a safety margin (LL+SM) and the high limit minus a safety margin (HL-SM); and,

    Varying $I_{d\text{-}\omega}$ between zero and 1 pu for rotor speeds between HL-SM and the HL; and,

    Varying $I_{d\text{-}\omega}$ between zero and -1 pu for rotor speeds between the LL + SM and LL.

10. A method of integrating and controlling SGs according to claims 4, 7, 8 and 9, in which I_{d-v}, I_{op}, and $I_{d-\omega}$ are added and multiplied by the NSC’s base current I_{base} to calculate the reference d-comment current I_d*, which is fed to a standard current control loop in the dq-frame.

Abstract

Synchronous generators (SGs) are the most popular type of generators that are used worldwide to generate electricity. There are two main types of SG: round-rotor (also known as turbo-generator) and salient-rotor. The principle of the operation of both types are the same: the rotor is connected to a mechanical source of energy, known as the prime mover, and rotates with it. Therefore, the rotating magnetic field (using either electro- or permanent magnet) of the rotor induce a voltage in the stator windings, which is connected to the load/grid. The prime movers for fossil/bio/nuclear fuelled power stations are either steam or gas turbines. SGs also are used as distributed generation units e.g. in CHP plants, where they are called microgenerators. The SGs are even used for renewable systems (e.g. wind), which are not the concern of this patent.

The ever-increasing penetration of Power Electronic Converter (PEC)-based generation units (e.g. renewable energy), has been causing numerous challenges for the network operators and has put the power networks on the verge of instability. Some of these challenges, which are due to the intermittent nature of renewable energy, do not depend on the power system structure. For example, as the penetration of renewable energy increases, more energy storage (ES) facilities will be needed to balance the generation with the demand (regardless of the system structure). However, there are some challenges (such as reduction in the short circuit level, phase angle movement, and rate-of-change-of-frequency) that do depend on the system structure. To alleviate these issues the popular approach (in both industry and academia) is to make the PECs behave like SGs. However, this approach is not optimized. For example, a SG can inject between 5-7 pu (per unit) fault current, known as short circuit level (SCL), while that of PEC-based unit is about 1.1-1.2 pu. Therefore, in order to be able to supply similar SCLs by the PEC-based units we must either “de-load” during normal operation or use over-sized power electronics switches. Neither de-loading nor using over-rated switches is an optimized solution and increase the energy price.

This patent proposes a “steer into the skid” strategy involving the decoupling of SGs from the network using AC/DC/AC PECs and controlling them such that the PECs impose the power on the SGs according to the local voltage and frequency (virtual AVR and virtual Governor).