

Some problems with connecting renewable energy sources to the grid

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Abstract—In this paper, we review some challenges resulting from the grid connection of powerful renewable energy generators that produce randomly fluctuating power and have no mechanical inertia. We propose and develop the idea of operating an inverter to mimic a synchronous generator. We call the inverters that are operated in this way synchronverters. Using synchronverters, the well-established theory/algorithms used to control synchronous generators can still be used in power systems where a significant proportion of the generating capacity is inverter-based. We describe the dynamics, implementation and operation of synchronverters. The real and reactive power delivered by synchronverters connected in parallel and operated as generators can be automatically shared using the well-known frequency and voltage drooping mechanisms. Synchronverters can be easily operated also in island mode and hence they provide an ideal solution for micro-grids or smart grids.

I. INTRODUCTION

For economic, technical and environmental reasons, the share of electrical energy produced by distributed energy sources, such as combined heat and power (CHP) plants, and renewable energy sources, such as wind power, solar power, wave and tidal power etc, is steadily increasing. As a result, the electrical power system is undergoing a dramatic change from centralized generation to distributed generation. Most of these distributed/renewable energy generators comprise variable frequency AC sources, high frequency AC sources or DC sources, and hence they need DC-AC converters, also called inverters, to interface with the public utility grid. For example, wind turbines are most effective if free to generate at variable frequency and so they require conversion from variable frequency AC to DC to AC; small gas-turbines with direct drive generators operate at high frequency and also require AC to DC to AC conversion; photo-voltaic arrays require DC-AC conversion. This means that more and more inverters will be connected to the grid and will eventually dominate power generation.

The current paradigm in the control of wind or solar power generators is to extract the maximum power from the power source and inject it all into the power grid; see for example [3], [2], [6]. Advanced algorithms have been developed to insure that the current injected into the grid is clean sinusoidal, see for example [16], [23]. Figure 1 shows the control loops in a typical DC to AC converter.

The policy of injecting all the available power to the grid is a good one as long as renewable power sources constitute

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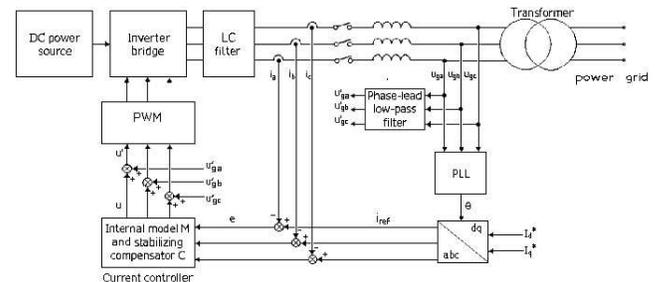


Fig. 1. A DC to AC (three phase) converter, modified from [23].

a small part of the grid power capacity. Indeed, any random power fluctuation of the renewable power generators will be compensated by the controllers associated with the large conventional generators, and some of these generators will also take care of overall power balance, system stability and fault ride-through.

When renewable power generators (especially the solar ones) will provide the majority of the grid power, such “irresponsible” behavior (on their part) will become untenable. Thus, the need will arise to operate them in the same way as conventional power generators, or at least to imitate certain aspects of the operation of conventional generators using novel techniques, see [18], [4], [14], [15], [17], [10], [19]. This will require high efficiency energy storage units, so that the random fluctuations of the prime power source can be filtered out. The key problem here is how to control the inverters in distributed power generators. There are two options: the first is to redesign the whole power system and to change the way it is operated (e.g., establish fast communication lines between generators and possibly central control) and the second is to find a way so that these inverters can be integrated into the existing system and behave in the same way as large synchronous generators (SG) do. We think that the second option has advantages, as it would assure a smooth transition to a grid dominated by inverters.

In this paper, we propose a method by which an inverter can be operated to mimic the behavior of a synchronous generator. The dynamic equations are the same, only the mechanical power exchanged with the prime mover (or with the mechanical load, as the case may be) is replaced with the power exchanged with the DC bus. We call such an inverter (including the filter inductors and capacitors) and the

associated controller a *synchronverter*. To be more precise, a synchronverter is equivalent to a synchronous generator with a small capacitor bank connected in parallel to the stator terminals. A synchronverter will have all the good and bad properties of a synchronous generator, which is a complex non-linear system. For example, among the undesirable phenomena, loss of stability due to under-excitation, as well as hunting (oscillations around the synchronous frequency) could occur in a synchronverter. An advantage is that we can choose the parameters such as inertia, friction coefficient, field inductance and mutual inductances. (The energy that would be lost in the virtual mechanical friction is not lost in reality, it is directed back to the DC bus.) Moreover, we can (and do) choose to have no magnetic saturation and no Eddy currents. If we want, we can choose parameter values that are impossible in a real synchronous generator, and we can also vary the parameters while the system is operating.

If a synchronverter is connected to the utility grid and is operated as a generator, no difference would be felt from the grid side between this system and an SG. Thus, the conventional control algorithms and equipment that have been developed for SGs driven by prime movers (and which have reached a high level of maturity over 100 years) can be applied to synchronverters. Synchronverters can also be operated as synchronous motors based on the same mathematical derivation. One option is to decide the direction of the energy flow between the DC bus and the AC bus in a synchronverter automatically according to the grid frequency. We think that synchronverters operated as synchronous motors will be useful, for example, in high voltage DC transmission lines, where DC power would be sent from a synchronverter working as a motor, to another one working as a generator at the other end of the line.

We mention that IEEE defined a term, called *static synchronous generator* [11], to designate a static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power. This term was originally defined for one of the shunt-connected controllers in FACTS (flexible AC transmission system). Clearly, synchronverters operated as generators would be a particular type of static synchronous generators.

There are papers in the literature exploring related ideas. The concept of a *virtual synchronous machine* (VISMA) was proposed in [1], where the voltages at the point of common coupling with the grid are measured to calculate the phase currents of the VISMA in real time. These currents are then used as reference currents for the inverter and hence the inverter behaves as a current source connected to the grid. If the current tracking error is small, then the inverter behaves like a synchronous machine, justifying the term VISMA. If the current tracking error is large, then the inverter behavior changes. They provided extensive experimental results (but the grid integration of VISMA using control algorithms for SG was left as future work). As a key difference to the

synchronverter, it is worth mentioning that the synchronverter does not depend on the tracking of reference currents or voltages. In [5], [20], a short-term energy storage system is added to the inverter in order to provide virtual inertia to the system. The power flow to the storage is proportional to the derivative of the grid frequency (as it would be with real inertia). This kind of inverters with added virtual inertia, called *virtual synchronous generators* (VSG), can contribute to the short-term stabilization of the grid frequency. However, the system dynamics seen from the grid side will be different from those of an SG.

The rest of the paper is organized as follows. In Section II, a dynamic model of SGs is established under no assumptions on the signals. Although the model of an SG is well documented in the literature, the way the model is described here is somewhat fresh. The way to implement a synchronverter is described in Section III and issues related to its operation, e.g., frequency and voltage drooping mechanisms for load sharing, are described in Section IV.

II. MODELING SYNCHRONOUS MACHINES

The model of synchronous machines can be found in many sources, such as [9], [8], [21], [13], [12]. Most of the references make various assumptions, such as steady state and/or balanced sinusoidal voltages/currents, to simplify the analysis. Here, we briefly outline a model that is a (non-linear) passive dynamic system without any assumptions on the signals, from the perspective of system analysis and controller design. We consider a round rotor machine, so that all stator inductances are constant. Our model assumes that there are no damper windings in the rotor, that there is one pair of poles per phase (and one pair of poles on the rotor), and that there are no magnetic saturation effects in the iron core and no Eddy currents. As is well known, the damper windings help to suppress hunting and also help to bring the machine into synchronism with the grid (see, for example, [12]). We leave it for later research to establish if it is worthwhile to include damper windings in the model used to implement a synchronverter. Our simulation and experimental results do not seem to point at such a need - we got negligible hunting, and we got fast synchronization algorithms without using damper windings.

A. The electrical part

For details on the geometry of the windings, we refer to [21], [8]. The field and the three identical stator windings are distributed in slots around the periphery of the uniform air gap. The stator windings can be regarded as concentrated coils having self-inductance L and mutual inductance $-M$ ($M > 0$ with a typical value $\frac{1}{2}L$, the negative sign is due to the $\frac{2\pi}{3}$ phase angle), as shown in Figure 2. The field (or rotor) winding can be regarded as a concentrated coil having self-inductance L_f . The mutual inductance between the field coil and each of the three stator coils varies with the rotor

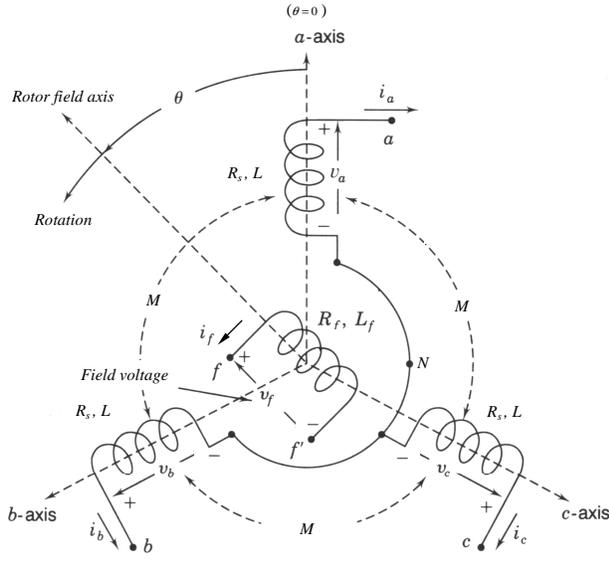


Fig. 2. Structure of an idealized three-phase round-rotor synchronous generator, modified from [9, Figure 3.4].

angle θ :

$$\begin{aligned} M_{af} &= M_f \cos(\theta), \\ M_{bf} &= M_f \cos\left(\theta - \frac{2\pi}{3}\right), \\ M_{cf} &= M_f \cos\left(\theta - \frac{4\pi}{3}\right), \end{aligned}$$

where $M_f > 0$. The flux linkages of the windings are

$$\begin{aligned} \Phi_a &= L i_a - M i_b - M i_c + M_{af} i_f, \\ \Phi_b &= -M i_a + L i_b - M i_c + M_{bf} i_f, \\ \Phi_c &= -M i_a - M i_b + L i_c + M_{cf} i_f, \\ \Phi_f &= M_{af} i_a + M_{bf} i_b + M_{cf} i_c + L_f i_f, \end{aligned}$$

where i_a , i_b and i_c are the stator phase currents and i_f is the rotor excitation current. Denote

$$\Phi = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix}, \quad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

and

$$\widetilde{\cos} \theta = \begin{bmatrix} \cos \theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}, \quad \widetilde{\sin} \theta = \begin{bmatrix} \sin \theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}.$$

Assume for the moment that the neutral line is not connected, then

$$i_a + i_b + i_c = 0.$$

It follows that the stator flux linkages can be rewritten as

$$\Phi = L_s i + M_f i_f \widetilde{\cos} \theta, \quad (1)$$

where $L_s = L + M$, and the field flux linkage can be rewritten as

$$\Phi_f = L_f i_f + M_f \langle i, \widetilde{\cos} \theta \rangle, \quad (2)$$

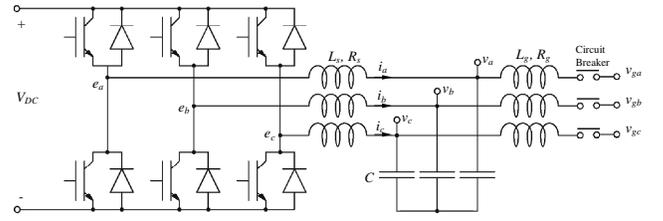


Fig. 3. The power part of a synchronverter is a three phase inverter, including LC filters.

where $\langle \cdot, \cdot \rangle$ denotes the conventional inner product in \mathbb{R}^3 . We remark that the second term $M_f \langle i, \widetilde{\cos} \theta \rangle$ (called armature reaction) is constant if the three phase currents are sinusoidal (as functions of θ) and balanced. We also mention that $\sqrt{\frac{2}{3}} \langle i, \widetilde{\cos} \theta \rangle$ is called the d -axis component of the current.

Assume that the resistance of the stator windings is R_s , then the phase terminal voltages $v = [v_a \ v_b \ v_c]^T$ can be obtained from (1) as

$$v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e, \quad (3)$$

where $e = [e_a \ e_b \ e_c]^T$ is the back emf due to the rotor movement given by

$$e = M_f i_f \widetilde{\sin} \theta - M_f \frac{di_f}{dt} \widetilde{\cos} \theta. \quad (4)$$

The voltage vector e is also called no-load voltage, or synchronous internal voltage.

We mention that, from (2), the field terminal voltage is

$$v_f = -R_f i_f - \frac{d\Phi_f}{dt}, \quad (5)$$

where R_f is the resistance of the rotor winding. However, we shall not need the expression for v_f because we shall use i_f , instead of v_f , as an adjustable constant input. This completes modeling the electrical part of the machine.

B. The mechanical part

The mechanical part of the machine is governed by

$$J \ddot{\theta} = T_m - T_e - D_p \dot{\theta}, \quad (6)$$

where J is the moment of inertia of all the parts rotating with the rotor, T_m is the mechanical torque, T_e is the electromagnetic torque and D_p is a damping factor. T_e can be found from the energy E stored in the machine magnetic field, i.e.,

$$\begin{aligned} E &= \frac{1}{2} \langle i, \Phi \rangle + \frac{1}{2} i_f \Phi_f \\ &= \frac{1}{2} \langle i, L_s i + M_f i_f \widetilde{\cos} \theta \rangle \\ &\quad + \frac{1}{2} i_f (L_f i_f + M_f \langle i, \widetilde{\cos} \theta \rangle) \\ &= \frac{1}{2} \langle i, L_s i \rangle + M_f i_f \langle i, \widetilde{\cos} \theta \rangle + \frac{1}{2} L_f i_f^2. \end{aligned}$$

From simple energy considerations (see, e.g., [8], [7]) we have

$$T_e = \left. \frac{\partial E}{\partial \theta} \right|_{\Phi, \Phi_f \text{ constant}}$$

(because constant flux linkages mean no back emf, hence all the power flow is mechanical). It is not difficult to verify (using the formula for the derivative of the inverse of a matrix function) that this is equivalent to

$$T_e = - \left. \frac{\partial E}{\partial \theta} \right|_{i, i_f \text{ constant}}.$$

Thus,

$$T_e = -M_f i_f \left\langle i, \frac{\partial}{\partial \theta} \widetilde{\cos \theta} \right\rangle = M_f i_f \left\langle i, \widetilde{\sin \theta} \right\rangle. \quad (7)$$

We mention that $-\sqrt{\frac{2}{3}} \left\langle i, \widetilde{\sin \theta} \right\rangle$ is called the q -axis component of the current. Note that if $i = i_0 \widetilde{\sin \varphi}$ for some arbitrary angle φ , then

$$T_e = M_f i_f i_0 \left\langle \widetilde{\sin \varphi}, \widetilde{\sin \theta} \right\rangle = \frac{3}{2} M_f i_f i_0 \cos(\theta - \varphi).$$

Note also that if i_f is constant (as is usually the case), then (7) with (4) yields

$$T_e \dot{\theta} = \langle i, e \rangle.$$

C. Provision of a neutral line

The above analysis is based on the assumption that the neutral line is not connected. If the neutral line is connected, then

$$i_a + i_b + i_c = i_N,$$

where i_N is the current flowing through the neutral line. Then, the formula for the stator flux linkages (1) becomes

$$\Phi = L_s i + M_f i_f \widetilde{\cos \theta} - \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} M i_N$$

and the phase terminal voltages (3) become

$$v = -R_s i - L_s \frac{di}{dt} + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} M \frac{di_N}{dt} + e,$$

where e is given by (4). The other formulas are not affected.

As we have seen, the provision of a neutral line makes the system model somewhat more complicated. However, in a synchronverter to be designed in the next section, M is a design parameter that can be chosen to be 0. The physical meaning of this is that there is no magnetic coupling between the stator windings. This does not happen in a physical synchronous generator but can be easily implemented in a synchronverter. When we need to provide a neutral line, it is an advantageous choice to take $M = 0$, as it simplifies the equations. Otherwise the choice of M and L individually is irrelevant, what matters is only $L_s = L + M$. In the sequel, the model of a synchronous generator consisting of (3), (4), (6) and (7) will be used to operate an inverter as a synchronverter.

III. IMPLEMENTATION OF A SYNCHRONVERTER

In this section, the details of how to implement a synchronverter will be described. A simple DC/AC converter (inverter) used to convert DC power into three-phase AC (or the other way round) is shown in Figure 3. It includes three inverter legs operated using pulse width modulation (PWM) and LC filters to reduce the voltage ripple (and hence the current ripple) caused by the switching. In grid connected operation, the impedance of the grid should be included in the impedance of the inductors L_g (with series resistance R_g), and then we may consider that after the circuit breaker we have an infinite bus. The circuit shown in Figure 3 does not provide a neutral line, but this can be added if needed. The *power part of the synchronverter* is the circuit to the left of the three capacitors, together with the capacitors. If we disregard the ripple, then this part of the circuit will behave like a synchronous generator connected in parallel with the same capacitors. The inductors denoted L_g are not part of the synchronverter, but it is useful to have them (for synchronization and power control). It is important to have some energy storage (not shown) on the DC bus (at the left end of the figure), since the power absorbed from the DC bus represents not only the power taken from the imaginary prime mover, but also from the inertia of the rotating part of the imaginary synchronous generator. This latter component of the power may come in strong bursts, proportional to the derivative of the grid frequency.

What we call the *electronic part of the synchronverter* is a digital signal processor (DSP) and its associated circuits, running under a special program, which controls the switches shown in Figure 3. Its block diagram is shown in Figure 4. These two parts interact via the signals e and i (v and v_g will be used for controlling the synchronverter). The various voltage and current sensors and the signal conditioning circuits and analog/digital converters should be regarded as part of the electronic part of the synchronverter. Normally, the program on the DSP will contain also parts that represent the controller of the synchronverter (not the synchronverter itself).

A. The power part

We give some ideas for the design of the power part. It is important to understand that the terminal voltages $v = [v_a \ v_b \ v_c]^T$ of the imaginary synchronous generator, as given in (3), are represented by the capacitor voltages shown in Figure 3. Further, the impedance of the stator windings of the imaginary synchronous generator is represented by the inductance L_s and the resistance R_s of the left inductors shown in Figure 3. It follows from here that e_a , e_b and e_c should represent the back emf due to the movement of the imaginary rotor. This is not possible exactly, because e_a , e_b and e_c are high frequency switching signals, but it is possible in the average sense: the switches in the inverter should be operated so that the average values of e_a , e_b and e_c over a switching period should be equal to e given in (4). This can be achieved by the usual PWM technique.

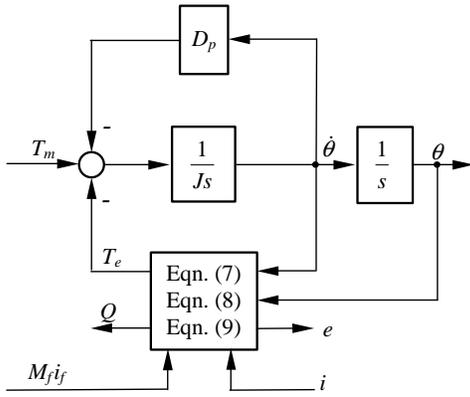


Fig. 4. The electronic part of a synchronverter (without control). This part interacts with the power part via e and i .

It is advantageous to assume that the imaginary field (rotor) winding of the synchronverter is fed by an adjustable DC current source i_f instead of a voltage source v_f . Then the terminal voltage v_f varies, but this is irrelevant. As long as i_f is constant, the generated voltage from (4) reduces to

$$e = \dot{\theta} M_f i_f \widetilde{\sin \theta}. \quad (8)$$

The filtering capacitors C should be chosen such that the resonant frequency $\frac{1}{\sqrt{L_s C}}$ is approximately $\sqrt{\omega_n \omega_s}$, where ω_n is the nominal angular frequency of the grid voltage and ω_s is the angular switching frequency used to turn on/off the switches (IGBTs are shown in the figure but other power semiconductors can be used as well).

If a neutral line is needed, then the strategies proposed in [24] or [22] to provide a neutral line without affecting the control of the three-phase inverter may be used.

B. The electronic part

Define the generated real power P and reactive power Q (as seen from the inverter legs) as

$$P = \langle i, e \rangle \quad \text{and} \quad Q = \langle i, e_q \rangle,$$

where e_q has the same amplitude as e but with a phase delayed from that of e by $\frac{\pi}{2}$, i.e.,

$$e_q = \dot{\theta} M_f i_f \widetilde{\sin(\theta - \frac{\pi}{2})} = -\dot{\theta} M_f i_f \widetilde{\cos \theta}.$$

Then, the real power and reactive power are, respectively,

$$\begin{aligned} P &= \dot{\theta} M_f i_f \langle i, \widetilde{\sin \theta} \rangle, \\ Q &= -\dot{\theta} M_f i_f \langle i, \widetilde{\cos \theta} \rangle. \end{aligned} \quad (9)$$

These coincide with the conventional definitions for real power and reactive power, usually expressed in d, q coordinates. Positive Q corresponds to an inductive load. Note that if $i = i_0 \widetilde{\sin \theta}$ for some angle φ (this would be the case, e.g., in balanced steady-state operation, with $\theta - \varphi$ constant), then

$$P = \dot{\theta} M_f i_f \langle i, \widetilde{\sin \theta} \rangle = \frac{3}{2} \dot{\theta} M_f i_f i_0 \cos(\theta - \varphi),$$

$$Q = -\dot{\theta} M_f i_f \langle i, \widetilde{\cos \theta} \rangle = \frac{3}{2} \dot{\theta} M_f i_f i_0 \sin(\theta - \varphi).$$

The above formulas for P and Q are used when regulating the real and reactive power of an SG.

The equation (6) can be written as

$$\ddot{\theta} = \frac{1}{J} (T_m - T_e - D_p \dot{\theta}),$$

where the mechanical (or active) torque T_m is a control input, while the electromagnetic torque T_e depends on i and θ according to (7). This equation, together with (7), (8) and (9), are implemented in the electronic part of a synchronverter shown in Figure 4. Thus, the state variables of the synchronverter are i (the inductor currents), v (the capacitor voltages), θ and $\dot{\theta}$ (which are a virtual angle and a virtual angular speed). (In the absence of a neutral line, only two of the three currents in the vector i are independent.) The control inputs of the synchronverter are T_m and $M_f i_f$. In order to operate the synchronverter in a useful way, we need a controller that generates the signals T_m and $M_f i_f$ such that system stability is maintained and the desired values of real and reactive power are followed. The significance of Q will be discussed in the next section.

IV. OPERATION OF A SYNCHRONVERTER

A. Frequency drooping and regulation of real power

For synchronous generators, the rotor speed is maintained by the prime mover and it is known that the damping factor D_p is due to mechanical friction. An important mechanism for SGs to share load evenly (in proportion to their nominal load) is to vary the real power delivered to the grid according to the grid frequency, which is a control loop called “frequency droop”. When the real power demand increases, the speed of the SGs drops due to increased T_e in (6). The power regulation system of the prime mover then increases the mechanical power, e.g., by widening the throttle valve of an engine, so that a new power balance is achieved. Typical values for the frequency droop are a 100% increase in power for a frequency decrease between 3% and 5% (from nominal values).

The frequency droop mechanism can be implemented in a synchronverter by comparing the virtual angular speed $\dot{\theta}$ with the angular frequency reference $\dot{\theta}_r$ (which normally would be equal to the nominal angular frequency of the grid $\dot{\theta}_n$), and adding this difference, multiplied with a gain, to the active torque T_m . The formulas show that the effect of the frequency droop control loop is equivalent to a significant increase of the mechanical friction coefficient D_p . In Figure 5 and later, the constant D_p represents the (imaginary) mechanical friction coefficient plus the frequency drooping coefficient (the latter is far larger). Thus, denoting the change in total torque acting on the imaginary rotor by ΔT , and the change in angular frequency by $\Delta \dot{\theta}$, we have

$$D_p = -\frac{\Delta T}{\Delta \dot{\theta}}.$$

It is worth noting that, in some references, such as [18], D_p is defined as $-\frac{\Delta \dot{\theta}}{\Delta T}$. Here, the negative sign is to make D_p

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