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Excerpt
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Part I

Context

1 Need for Energy Storage

1.1 Introduction

Storage is a fundamental part of any system. Goods are stored in warehouses. Internal combustion engines utilise fuel to store energy. Computers need hard disks. Communication systems and internet networks require data concentrators. Biological cells utilise adenosine triphosphate. Hydrogen is the fuel of stars. Ultimately, all matter stores energy according to the well-known mass–energy equivalence, as deduced from the special relativity postulates and the symmetries of space and time.

This book focuses exclusively on electric system applications and only on those particular kinds of energy storage technologies that are able to *cycle* the energy. The chemical energy stored in fossil fuel is not part of what we consider hereinafter as energy storage devices. We look for storage technologies which are also fully *reversible*, except of course for inevitable losses. A byproduct of the energy storage technologies and devices considered in this book is to reduce the *grey energy* due to fossil fuels.

Electric systems naturally include several kinds of energy storage, spanning several time scales. This book focuses on the specific mechanism to store and exchange energy through power electronic converters in the time scales from a few hundred milliseconds to tens of minutes. Electromechanical and control dynamics fall within these time scales. The focus is not on how energy is stored *per se* but, rather, how stored energy can be efficiently and conveniently exchanged during power system transients.

The remainder of this chapter discusses the crucial role of energy storage for power systems in the relevant time scales. In particular, the chapter provides a high level overview of the *natural* energy storage in power systems. Section 1.2 shows that energy storage is a fundamental, intrinsic part of such systems. There are, in fact, several time scales and means where energy is stored. Without such storage means, the systems cannot work. Seven quantitative examples are provided. Section 1.3 discusses the impact of the integration of renewable energy resources and elaborates on the effects of reducing the inertia due to non-synchronous generation. The concept of flexibility is also discussed in this section. Section 1.4 states the need for new devices to store energy and why such devices are more important today than ever in the history of power systems. Section 1.5 discusses the features and roles of conventional and converter-interfaced energy storage devices. Section 1.6 proposes a variety of symbols for generic converter-interfaced energy storage devices for single-line electric diagrams.

1.2 Power Balance in Electric Energy Systems

One of the first concepts taught in a module on electrical energy systems is that power consumption and losses have to be balanced at every instant by generation. This statement allows introducing the need for frequency control, power reserve and, on a longer time scale, unit commitment and seasonal storage.

After providing this example, the lecturer often also proposes to the students some counter-examples of other systems that do not have such a strict power balance requirement. In the internet, if the download requests of a user cannot be satisfied, they simply wait until the communication band is less congested. Similarly, in the transport sector, traffic jams happen and people simply have to wait until roads again become accessible. The list of counter-examples completes with saying that, in power systems, a load cannot 'wait' for the congestion to be resolved and this makes the control of a power system quite challenging.

While fundamentally correct, the statement above lacks some important remarks and clarifications which are crucial for this book and constitute its motivation. The first remark is that balancing the variations of the load cannot be achieved 'instantaneously', even assuming an ideal control. The control can only 'follow' load variations and there is no way to perfect tracking load variations. To complicate the situation, in recent years part of the generation has also become stochastic – because of the penetration of wind and solar power – and the balance of the consumption/losses/generation has become even more challenging.

The question is thus: how is the power balanced during the inevitable time that elapses from the load variation and the action of the fastest control? Loads have actually to 'wait' for their demand to be satisfied. Only such a wait is way shorter than what may happen in congested internet and road networks. The physical principle, however, is the same. As soon as the load consumption increases, the extra energy required is harvested from the energy stored in the system itself. In the same vein, if the load consumption decreases, the surplus of energy temporarily available is stored in the system.

It has to be expected that this energy storage process back and forth within the system cannot take too long. In engineering, the concepts of *long* and *short* – as well as those of *big* and *small* – are relative. The time scale of the phenomenon considered here is in the range of a few hundred milliseconds up to a few seconds. This is the equivalent in power systems of the several minutes that the download of a large film from the internet can take and the hours that a traffic jam can last. If the frequency control does not intervene within a few seconds, then the electric system can face serious stability issues and even collapse. The blackout in Europe in 2006 is a good example of what happens if the frequency control fails [28].

So far, we have focused only on the instantaneous power balance. Power system dynamics and operation, however, span several time scales, from milliseconds to years. Depending on the time scale, different devices and/or controllers take over the role of handling the energy storage. Storage is crucial for every time scale. Without storage, the whole system would crash as a house of cards.

The centrality of the role of energy storage is the common thread of this book. Let us illustrate this concept with some examples, as follows:

1 ms	: electromagnetic transient of a long transmission line.
10 ms	: charge and discharge of the capacitor on the DC side of an AC/DC converter.
100 ms	: transient response of the DC exciter of a large synchronous generator.
1 s	: electromechanical oscillations of synchronous machines.
10 s	: primary frequency control of synchronous machines.
100 s	: secondary frequency control of synchronous machines.
1 h	: load levelling through pumped hydroelectric power plants.

These examples span relevant time scales of power system dynamics, control and operation.

1.2.1 Example 1: Storage in Transmission Lines

Three-phase AC transmission systems are huge RLC circuits where resistances, inductances and capacitances are due to, respectively, transmission losses; conductor inductive effects and transformer flux leakages and magnetisation; and overhead line and cable parasite capacitive charging.

This example discusses the ability of transmission lines to store energy and release it to the load during a voltage dip. Let us consider the simplified lumped π-model of the transmission line shown in Figure 1.1 (see Section 4.3.1 for further details on the model of the transmission system).

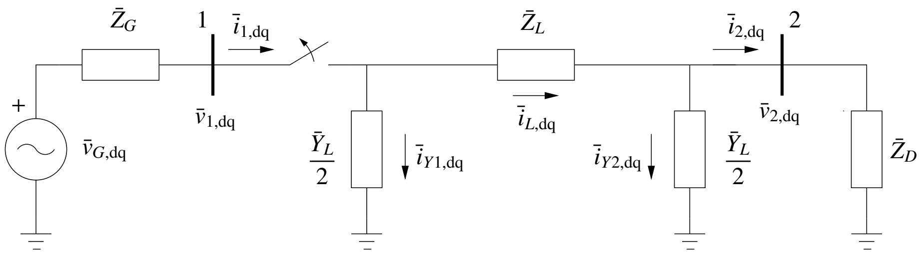


Figure 1.1 Simplified transmission system including a voltage source that feeds a load through an overhead transmission line.

This first example is rather unconventional as the primary purpose of three-phase AC circuits in general and of transmission lines in particular is to transmit energy from the generators to the loads, not to store such energy. As a matter of fact, transmission lines are not the best energy storage systems as we show below. It is considered important, however, to provide a quantitative example and show the effective time scale of the discharge of a line. We trust that associating ‘numbers’ to the concepts is useful to avoid gross misunderstandings and have a better idea of the actual behaviour of the electrical system and its components.

Table 1.1 Equivalent π-circuit parameters per phase for long transmission lines at 60 Hz [11].

Length, ℓ [km]	R_L [Ω]	X_L [Ω]	$G_L/2$ [μS]	$B_L/2$ [μS]
200	3.64573	73.74022	0.1260473	449.89134
400	6.80630	142.59986	1.0503017	915.21820
600	9.04484	202.02055	3.8012269	1,413.60348
800	10.01682	248.96718	9.9799844	1,967.73599

The parameters of the line are indicated in Table 1.1 and represent the equivalent π-model parameters for a standard long transmission line [11]. The load connected to bus 2 is assumed to be purely resistive, i.e. $\bar{Z}_D = R_D$ and consumes the rated current at the nominal voltage. Finally, the source is a constant 550 kV, 60 Hz voltage generator and is assumed to be the phase reference:

$$\bar{v}_{G,\mathrm{dq}} = \frac{\sqrt{2}}{\sqrt{3}}\, 550 + j0 \text{ kV} , \tag{1.1}$$

where the dq-axis magnitude is assumed to be the peak value of the Root Mean Square (RMS) phase-to-neutral voltage and the equivalent Thévenin equivalent impedance per phase of the source is set as:

$$\bar{Z}_G = 10\ \Omega/\text{phase} . \tag{1.2}$$

The equations of the circuit in dq-frame coordinates rotating at ω_o are:

$$\begin{aligned}
0 &= \bar{v}_{G,\mathrm{dq}} - R_G\, \bar{i}_{1,\mathrm{dq}}(t) - \bar{v}_{1,\mathrm{dq}}(t) \\
0 &= \bar{i}_{1,\mathrm{dq}}(t) - \bar{i}_{Y1,\mathrm{dq}}(t) - \bar{i}_{L,\mathrm{dq}}(t) \\
0 &= 0.5\, B_L \left(\frac{\mathrm{d}}{\mathrm{d}t} + j\omega_o\right) \bar{v}_{1,\mathrm{dq}}(t) + 0.5\, G_L\, \bar{v}_{1,\mathrm{dq}}(t) - \bar{i}_{Y1,\mathrm{dq}}(t) \\
0 &= \bar{v}_{1,\mathrm{dq}}(t) - \bar{v}_{2,\mathrm{dq}}(t) - R_L\, \bar{i}_{L,\mathrm{dq}}(t) - X_L \left(\frac{\mathrm{d}}{\mathrm{d}t} + j\omega_o\right) \bar{i}_{L,\mathrm{dq}}(t) \\
0 &= \bar{i}_{L,\mathrm{dq}}(t) - \bar{i}_{Y2,\mathrm{dq}}(t) - \bar{v}_{2,\mathrm{dq}}(t) \\
0 &= 0.5\, B_L \left(\frac{\mathrm{d}}{\mathrm{d}t} + j\omega_o\right) \bar{v}_{2,\mathrm{dq}}(t) + 0.5\, G_L\, \bar{v}_{2,\mathrm{dq}}(t) - \bar{i}_{Y2,\mathrm{dq}}(t) \\
0 &= \bar{v}_{2,\mathrm{dq}}(t) - R_D\, \bar{i}_{2,\mathrm{dq}}(t) ,
\end{aligned} \tag{1.3}$$

where

$$\begin{aligned}
\bar{Z}_L &= R_L + jX_L \\
\bar{Y}_L &= G_L + jB_L ,
\end{aligned} \tag{1.4}$$

are the series impedance and the shunt admittance, respectively, of the transmission line (see also Section 4.3.1.1), and $\omega_o = 2\pi f_o = 2\pi\, 60 = 377$ rad/s is the fundamental angular speed of the system.

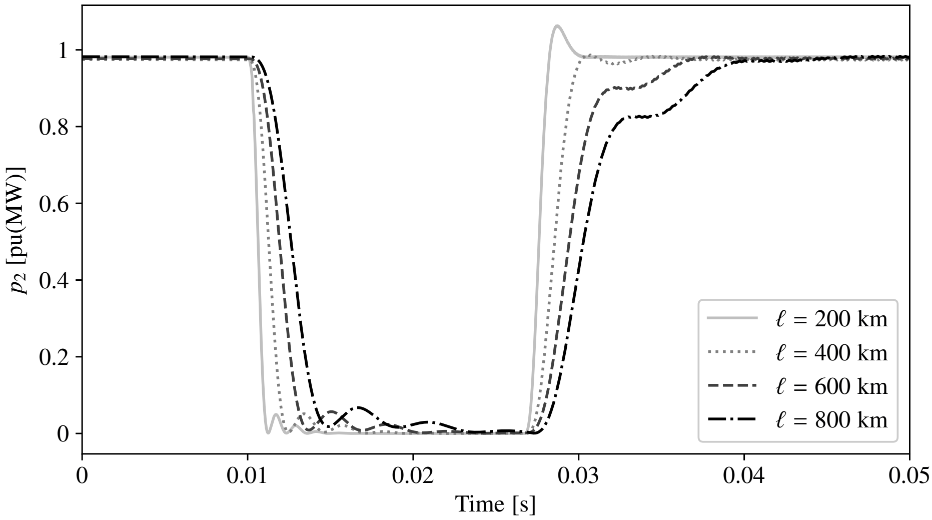


Figure 1.2 Effect of the line length on the power consumed by the load connected to bus 2 following the disconnection of the source at $t = 0.01$ s during 1 cycle. ℓ is the length of the transmission line. The power base is 500 MVA.

Figure 1.2 shows the dynamic behaviour of the power consumed by the load connected to bus 2 after the disconnection of the source at $t = 0.01$ s during 1 cycle, namely 16.7 ms at 60 Hz. As expected, the transmission line, even if very long, is not able to sustain the power of the load with the energy stored in its equivalent impedance and capacitance. The discharge of the line stored energy lasts, in the best scenario, a few milliseconds. Despite its fast discharge rate, this energy prevents the power instantaneously dropping to zero during the transient and is thus useful to reduce the effects of micro imbalances in the load and 'helps', along with the energy stored in machine fluxes, cope with the very first instants after a disturbance.

1.2.2 Example 2: Capacitive Storage

The RC circuit shown in Figure 1.3 includes an electrostatic storage. When the switch is closed, the equation that models the circuit is:

$$C \frac{\mathrm{d}}{\mathrm{d}t} v(t) = \frac{1}{R_1}\big(v_o - v(t)\big) - \frac{1}{R_2}\, v(t) \,. \tag{1.5}$$

When the switch is open, one has:

$$C \frac{\mathrm{d}}{\mathrm{d}t} v(t) = -\frac{1}{R_2}\, v(t) \,. \tag{1.6}$$

As long as the switch is closed, the capacitor stores energy in the form of electric charge on its plates, whereas it releases energy when the switch is open. This concept is well-known to any first year engineering student, of course. However, it is important to emphasise the role of the capacitor and, hence, of the energy storage in the circuit.

If the circuit did not include the capacitor, during the dip the power delivered to the resistance R_2 would be null during the voltage dip. The capacitor can release its stored energy and, hence, the current flowing in the resistance R_2 is non-null when the voltage source is disconnected, provided that the capacitance is *big enough* and the dip duration is *short enough*.

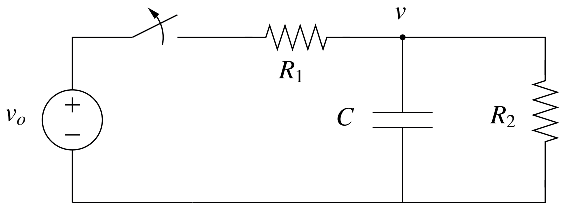


Figure 1.3 Simple RC circuit with a constant voltage source v_o and a switch that interrupts the supply.

The RC circuit shown in Figure 1.3 can model the capacitor on the DC side of an AC/DC converter. Such a capacitor is required to reduce the voltage ripple due to the converter switching and provide fault-ride-through capability during at least half a cycle of the AC fundamental frequency. For a converter with rated power $p_n = 1$ MW and voltage $v_n = 800$ V, the capacitor is of the order of tens of millifarads.

In power converters, the DC capacitor is designed for either (i) reducing the ripple due to the converter switching; or (ii) enabling a fault-ride-through capability when operating as a current source converter (CSC). Generally criterion (ii) provides larger values for the capacitance.

For the fault-ride-through design, typical hypotheses are that the converter is operating as CSC and that it should at least withstand a voltage dip of 100% for a duration of half a cycle, e.g. $t_{1/2} = 10$ ms. It is assumed that, before the voltage dip, the DC bus voltage is the rated one and that the converter is delivering its rated power. During the dip, the voltage on the DC bus is entirely sustained by the DC capacitor until a minimum voltage value, $v_{\rm dc}^{\rm min}$, below which the converter is disconnected.

The assumptions above lead to the following constraint:

$$p_n \, t_{1/2} = \frac{1}{2} C \, (v_n^2 - v_{\rm dc}^{\rm min\,2}) \,, \tag{1.7}$$

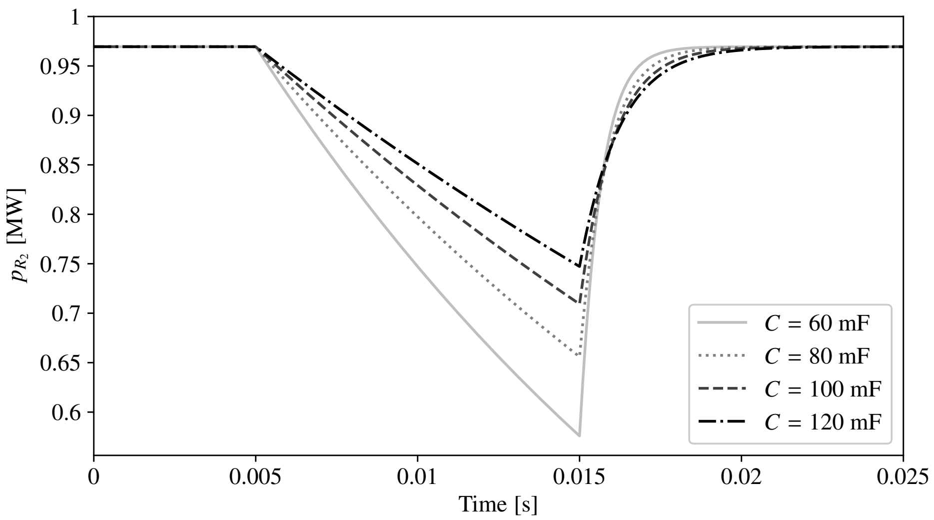
and, substituting the values above for p_n, v_n and $t_{1/2}$, and assuming that $v_{\rm dc}^{\rm min} = 600$ V, (1.7) gives:

$$10^6 \cdot 0.01 = \frac{1}{2} C(800^2 - 600^2) \,,$$

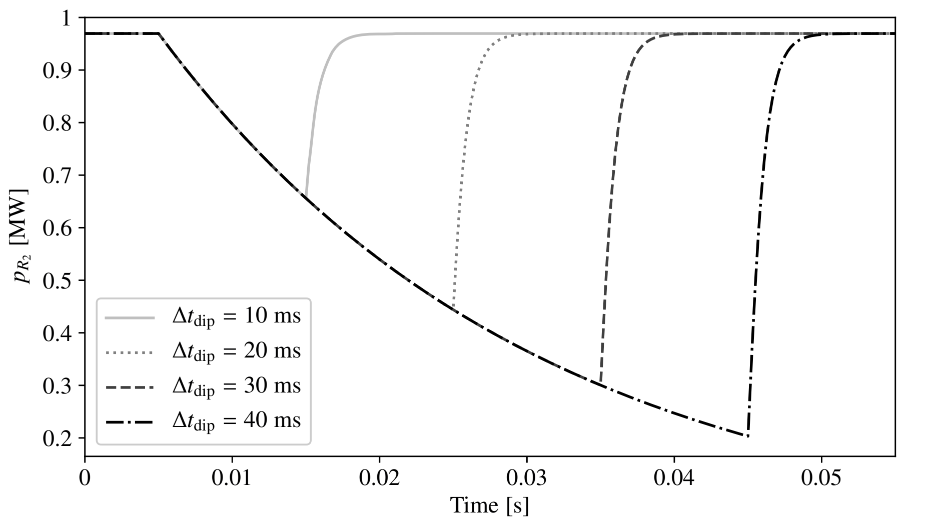
which leads to $C = 7.14 \cdot 10^{-2}$ F.

Back to the circuit of Figure 1.3, assume that the resistance R_2 models a load that consumes 1 MW at the rated voltage, i.e. $R_2 = v_n^2/p_n = 0.64\ \Omega$; and $v_o = v_n$ and $R_1 = 1\ \Omega$ is the Thévenin equivalent voltage and resistance, respectively, of the DC voltage source that feeds the load. Finally, assume that the time during which the switch is open, namely $\Delta t_{\rm dip}$, is a multiple of half a cycle of a 50 Hz system.

Figure 1.4a shows the power dissipated by R_2 during the transient for different values of the capacitance C and same duration $\Delta t_{\mathrm{dip}} = 10$ ms of the voltage dip. Figure 1.4b shows the power dissipated by R_2 during the transient for a fixed value of the capacitance $C = 80$ mF and different lengths Δt_{dip} of the voltage dip.



(a) Comparison for different capacitances



(b) Comparison for different voltage dip durations

Figure 1.4 Power dissipated in the resistance R_2 as a function of: (a) the value of the capacitance C following a voltage dip of duration $\Delta t_{\mathrm{dip}} = 10$ ms starting at $t = 5$ ms; and (b) the duration of the voltage dip Δt_{dip} for a capacitor $C = 80$ mF. The voltage dip is caused by the opening of the switch occurring at $t = 5$ ms.

The key aspects of these otherwise quite expected results are the *size* of the capacitance and the *duration* of the dip. It is clear that the power in the resistance R_2 will not drop to zero only if the dip lasts for a sufficiently short time and/or the capacitance is sufficiently big. Another fundamental parameter that decides the response of the circuit is the *initial charge* of the capacitor. The simulation results shown in Figure 1.4 have been obtained assuming that the capacitance is fully charged at $t = 0$, and hence the energy initially stored in the capacitance is

$$E_{C,o} = \frac{1}{2}\, C\, \frac{R_2^2}{(R_1 + R_2)^2}\, v_o^2 \approx \frac{1}{2}\, C\, v_n^2 \,, \tag{1.8}$$

where $\frac{R_2}{R_1+R_2} v_o \approx v_n$ is the voltage on the capacitor in steady state with the switch closed, as can be deduced from (1.5). For example, assuming $C = 80$ mF, $E_{C,o} = 24.8$ kJ, i.e. about 2.5% of the energy consumed by the load in 1 s. It is also relevant to note that C and R_2 are directly and inversely proportional to the rated power of the converter, respectively, so the time constant and, hence, the response time of the circuit does not actually vary.

We have chosen the parameters of the circuit to show a realistic transient behaviour of the capacitor connected to the DC side of an AC/DC converter on purpose. The goal is to remove any doubt about the fact that the energy storage capability of these devices alone is limited both in terms of duration (about a cycle) and in terms of energy (a small percentage of the rated converter capacity). The need for dedicated energy storage devices to be connected to the DC side of the converters is thus apparent.

1.2.3 Example 3: Inductive Storage

Let us consider a dual example with respect to the RC circuit above. The RL circuit shown in Figure 1.5 includes magnetic storage in the form of a conventional iron-core winding. When the switch is open, the inductance stores magnetic energy in its core according to the equation:

$$L\, \frac{\mathrm{d}}{\mathrm{d}t} i(t) = R_1 \big(i_o - i(t)\big) - R_2\, i(t) \,. \tag{1.9}$$

When the switch is closed, the circuit is described by the following equation:

$$L\, \frac{\mathrm{d}}{\mathrm{d}t} i(t) = -R_2\, i(t) \,, \tag{1.10}$$

and the inductance prevents the current that flows in the resistance R_2 from dropping instantaneously by releasing the stored magnetic energy.

Let us assume that the circuit represents the main exciter of a round rotor synchronous generator. The machine nominal values are $s_n = 588$ MVA, $p_n = 500$ MW, $v_n = 21$ kV, and $f_n = 50$ Hz. The exciter nominal current and voltage are $i_n = 6{,}300$ A and $v_n = 600$ V, respectively. The inductance of an exciter of this size is typically around a few hundred mH.

No load is generally connected to the exciter but, for the sake of example, let assume that R_2 represents a resistive load that consumes the rated active power of the generator,