MODELING OF ELECTRONICALLY INTERFACED DISTRIBUTED ENERGY RESOURCES FOR TRANSIENT ANALYSIS

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Contents

Summary

As they penetrate more, distributed energy resource (DER) systems are expected to make impressions on the steady-state and transient characteristics of their host power systems. This expectation has necessitated impact assessment simulation studies, by manufacturers, consultants, system integrators, and host utility companies. This chapter takes a brief look at the development of circuit-based simulation models for electronically coupled DER systems, and suggests a generic approach. The chapter discusses the need for the recognition of transient and steady-state phenomena that a simulation model is expected to capture, and that the developed models should be adequate while they avoid unnecessary details. The concepts are illustrated by an example.

1. Introduction

For a variety of technical, economical, and environmental reasons, the electric power system is receiving small-scale distributed generation (DG) and distributed storage (DS) systems at its low- and medium-voltage levels of operation. Consequently, DG and DS systems, which are collectively referred to as *distributed energy resource* (DER) systems, are expected to affect the power system transients, especially as their aggregate installed capacity continues to grow. This expectation indicates the need for modeling, simulation, and analysis techniques to reveal the steady-state and transient impacts of DER systems on the power system.

Broadly speaking, DER systems can be classified under rotating-machine-based DER systems and electronically interfaced DER systems. A rotating-machine-based DER system employs a synchronous or asynchronous (induction) generator to convert mechanical energy to electricity. More importantly, the electric machine is directly coupled with the host power system and thus bound to operate at the power system frequency; some examples include biomass-fuelled generators, diesel-fuelled generators, generators driven by gas-fuelled internal combustion engines, small hydroelectric generators, and constant-speed wind energy systems. By contrast, an electronically interfaced DER system may or may not utilize a rotating machine to generate electricity out of the prime energy resource. Regardless, its electricity generation component is coupled with the power system via a power-electronic interface, and not directly. The main reason is that many energy resources generate either dc power or ac power at a different or even variable frequency with respect to the power system frequency. The best known examples of electronically interface DER systems are photovoltaic (PV) solar energy systems, fuel-cell systems, variable-speed wind energy systems, battery energy storage systems, supercapacitor energy storage systems, and flywheel energy storage systems. It should be noted that the boundary between the two aforementioned classes is not crisp. For example, a generator driven by an internal combustion engine may be equipped with a power-electronic interface, in order to be capable of variable-speed operation and thus running optimally in various operating conditions.

This chapter is concerned with electronically interfaced DER systems. Using a generic model, the chapter first introduces the construction and principles of operation of an electronically interfaced DER system; it will be discussed that different electronically interfaced DER systems can be considered as special cases of the generic model. Then, important transients pertaining DER systems are introduced. Finally, a number of modeling techniques for capturing different transients are discussed using the example of a PV energy system.

2. Generic Electronically Interfaced DER System

Figure 1 illustrates a generic schematic diagram of an electronically interfaced DER system. The DER system consists of an energy resource and a power-electronic interface, which are interconnected from their dc ports. The energy resource, for example, an array of PV modules or batteries, exchanges the power P_{ext} with the power-electronic interface. In turn, the power-electronic interface consists of a dc-ac power-electronic converter, the dc-side capacitor C, an ac-side filter to mitigate harmonic current injection by the converter, and a start-up/shut-down switchgear. The power-electronic interface exchanges the real and reactive powers P_g and Q_g with the host grid. Although a three-phase configuration is implied in Figure 1, the converter (and its filter and switchgear) can be single-phase.

Figure 1 also illustrates the control architecture of the power-electronic interface. The converter is switched based on the pulse-width modulation (PWM) strategy, enabling rapid control of the magnitude and phase angle of the converter ac-side terminal voltage, v_t. The aforementioned process is then employed in a dedicated feedback loop that controls the magnitude and phase angle of the converter ac-side current i_t, relative to those of the power system voltage v. This, in turn, enables the regulation of P_g and Q_g at their corresponding setpoints (not shown in Figure 1). It should be mentioned that it is also possible to directly control P_g and Q_g by the magnitude and phase angle of v_t. The strategy, known as the *voltage-mode control* approach, however, renders the converter vulnerable to overcurrents (whether in transient or steady-state regimes) as well as to network faults. By contrast, the *current-mode control* method described earlier avoids the aforementioned vulnerability by allowing for the imposition of a safe upper limit on the magnitude of i_t and is, therefore, widely adopted. The current-control method is assumed for the remainder of our discussion.

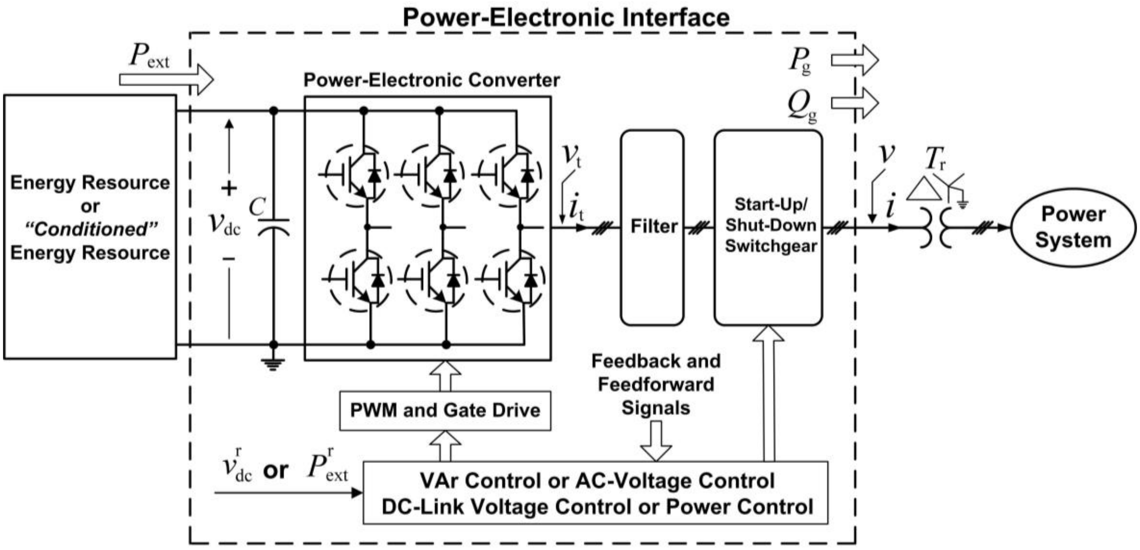

Figure 1. Generic schematic diagram of an electronically interfaced distributed energy resource (DER) system

The capability to control P_g and Q_g permits a number of possible control and operating scenarios for the DER system of Figure 1, as explained below.

- Q_g can be regulated at a pre-specified value, including zero for unity power-factor operation of the DER system. We refer to this control mode as the *VAr control mode*;

- Alternatively, Q_g can be actively controlled by a feedback loop that regulates the magnitude of v. This mode of control is referred in this chapter to as the *AC-voltage control mode*;
- P_g can be controlled to regulate the dc-link voltage v_{dc} at its setpoint v_{dc}^r, if the energy resource is of the current-source nature. For example, if the energy resource is a PV array, v_{dc} can be controlled to maximize the energy resource power output P_{ext}; the process is better known as the maximum power-point tracking (MPPT) and determines v_{dc}^r. We refer to this control mode as the *dc-link voltage control mode*; and
- Alternatively, if the energy resource is of the voltage-source nature, the dc-link voltage is imposed and cannot be controlled. Rather, the power output P_{ext} is the variable that can be regulated at its setpoint P_{ext}^r, by controlling P_g. For example, if the energy resource is a battery bank, P_{ext} is controlled according to the prevailing charging/discharging regime of the battery energy storage system. This control mode is referred in this chapter to as the *power control mode*.

The structure and design of the controllers for each of the aforementioned control modes are extensively discussed by Yazdani & Iravani (2010). It should be noted that, irrespective of the control mode, the steady-state values of P_g and P_{ext} are approximately equal due to the typically large efficiency of the power-electronic interface.

Figure 1 also indicates that the DER system may alternatively employ a *conditioned energy resource*. As illustrated in Figures 2(a) and (b), a conditioned energy resource is one that precedes an intermediate electronic power conditioner. In the system of Figure 2(a), the energy resource generates dc power and thus a dc-dc electronic power conditioner is utilized, whereas Figure 2(b) represents a system in which the energy resource generates single- or three-phase ac power and, therefore, the power-electronic conditioner is an ac-dc converter.

In both systems, the dc terminals of the power-electronic conditioner define the dc port of the conditioned energy resource. The conditioning power converter may be based on a variety of configurations. For example, in some low-power wind energy systems, the ac-dc conditioning converter consists of a diode-bridge rectifier and a dc-dc boost converter (see Section 3.6, Figure 4).

Based on the configurations of Figures 2(a) and (b), a conditioned energy resource is of the current-source nature. Therefore, with reference to our earlier discussion about the control of the DER system of Figure 1, one must exercise the dc-link voltage control mode and regulate v_{dc} at an optimal fixed value. Consequently, P_{ext} is controlled by the control scheme of the power-electronic conditioner, as illustrated in Figures 2(a) and (b), usually with the objective of maximizing P_{ext} through an MPPT algorithm (such as in variable-speed wind energy systems or two-stage PV energy system), or based on another criterion.

It is worth mentioning that the conditioning of an energy resource, as described above, is usually exercised (1) to enable the integration of energy resources with low-voltage outputs, as in the cases of fuel cells and supercapacitors; (2) to enable MPPT, as in the cases of variable-speed wind energy systems and two-stage PV energy systems; or (3) to allow for optimal operation of the power-electronic interface of the DER system, as in the case of two-stage PV systems. The trade-off, however, is the somewhat lower efficiency of a DER system with a conditioned energy resource, as compared with a single-stage DER system, due to the existence of two power-electronic converters.

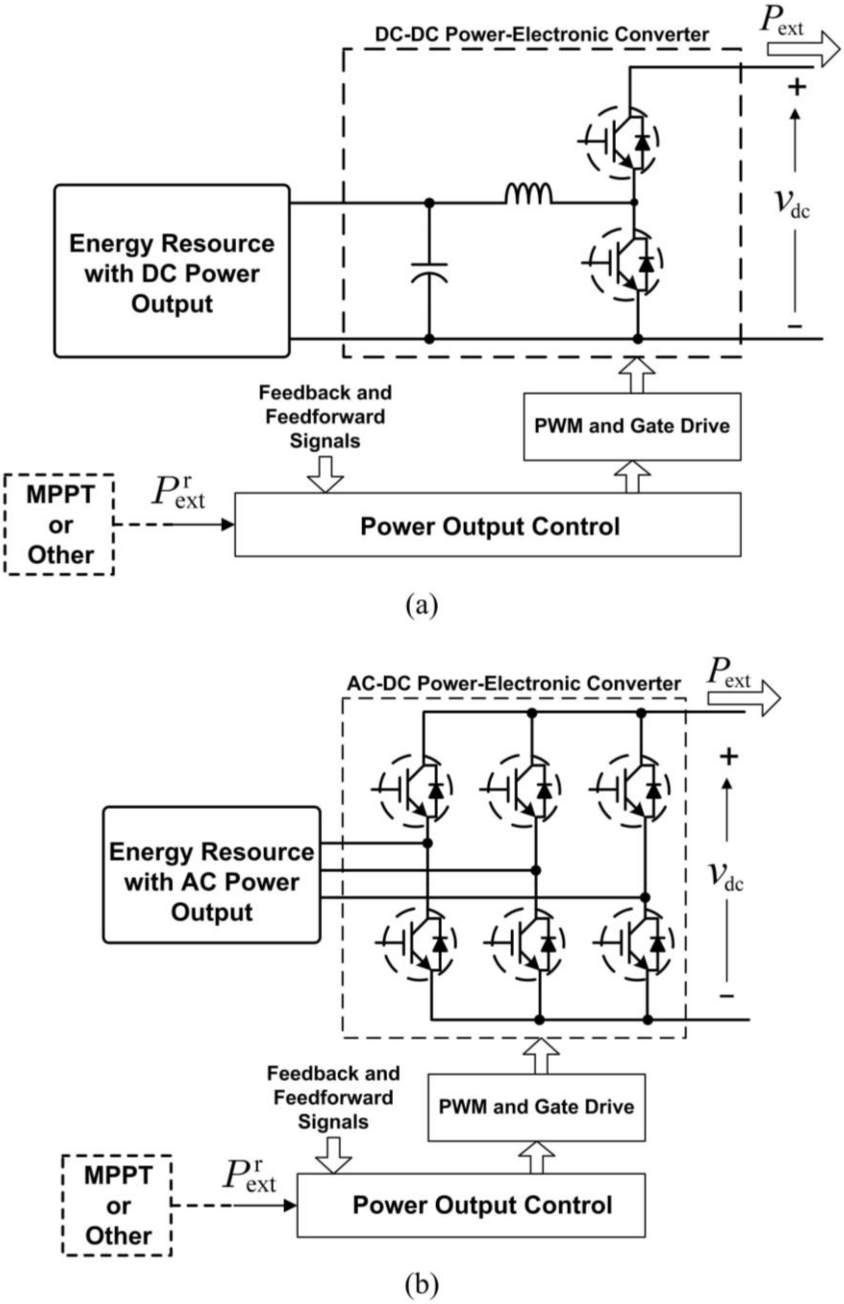

Figure 2. Generic schematic diagrams of (a) a *conditioned dc energy resource*, and (b) a *conditioned ac energy resource*

3. Realization of Different DER Systems

This section discusses different DER system realizations based on the generic model of Figure 1.

3.1. PV Energy Systems

Grid-connected PV energy systems can be classified under single-stage and two-stage systems. A single-stage PV system adheres to the generic model of Section 2 if the energy resource in Figure 1 is replaced with an array of series- and parallel-connected PV modules. The control mode is thus that of dc-link voltage control mode (see Section 2) and v_{dc}^{r} is determined by an MPPT scheme. Similarly, a two-stage PV energy system can also be realized based on the architecture of Figure 1. However, in a two-stage PV system, the energy resource, i.e., the PV array, is conditioned by a dc-dc boost converter, as shown in Figure 2(a). To control the two-stage PV system, the setpoint v_{dc}^{r} in Figure 1 is set to a fixed positive value, corresponding to the dc-link voltage control mode, while P_{ext}^{r} in Figure 2(a) is determined through an MPPT process. In a decentralized two-stage PV system where a multitude of PV arrays are conditioned by corresponding dc-dc converters, multiple conditioned energy resources of the form shown in Figure 2(a) are connected in parallel with the dc port of the power-electronic interface of Figure 1.

3.2. Fuel-Cell Systems

A fuel-cell system also adheres to the generic model of Figure 1 and the conditioned energy resource model of Figure 2(a). Thus, the resultant DER system is controlled such that v_{dc}^{r} in Figure 1 is set to a fixed positive value, corresponding to the dc-link voltage control mode (Section 2), while P_{ext}^{r} in Figure 2(a) is determined based on a desired power dispatch strategy.

3.3. Battery Energy Storage Systems

Similar to PV systems, battery energy storage systems can be single-stage or two-stage systems. In a single-stage battery energy storage system, the energy resource in Figure 1 is an array of series- and parallel-connected batteries, and one must exercise the power control mode (see Section 2). Therefore, P_{ext}^{r} is determined based on the battery charging/discharging requirements and the power deployment strategy. In a two-stage energy storage system, however, the battery bank is conditioned as shown in Figure 2(a), and P_{ext}^{r} is determined based on the battery charging/discharging requirements and the power deployment strategy; the setpoint v_{dc}^{r} in Figure 1 is set to a fixed positive value, corresponding to the dc-link voltage control mode.

Irrespective of the number of stages, an auxiliary feedback loop may be included to override P_{ext}^{r} if the battery bank voltage exceeds a maximum permissible value when the batteries are being charged, or if the voltage drops below a minimum threshold when the batteries are being discharged.

3.4. Supercapacitor Energy Storage System

For a supercapacitor energy storage system, the energy resource in Figure 1 is an array of supercapacitors and conditioned as shown in Figure 2(a). Thus, $v_{\mathrm{dc}}^{\mathrm{r}}$ in Figure 1 is set to a fixed positive value, corresponding to the dc-link voltage control mode (Section 2), while $P_{\mathrm{ext}}^{\mathrm{r}}$ in Figure 2(a) is determined based on the charging/discharging requirements and the power deployment strategy. Further, an auxiliary feedback loop is needed to override $P_{\mathrm{ext}}^{\mathrm{r}}$ if the capacitor bank voltage exceeds a maximum permissible value when the capacitors are being charged.

3.5. Superconducting Magnetic Energy Storage System

The energy resource in a superconducting magnetic energy storage (SMES) system is conditioned. However, it differs from the scheme of Figure 2(a) in the sense that its dc-dc power conditioner is typically a full-bridge converter, as shown in Figure 3. Even though the full-bridge converter of Figure 3 is shown in full detail, two of its diagonal transistors may be omitted from the valves of the power-electronic conditioner (Ise, Kita, & Taguchi 2005), since the direction of the coil current does not have to be reversed.

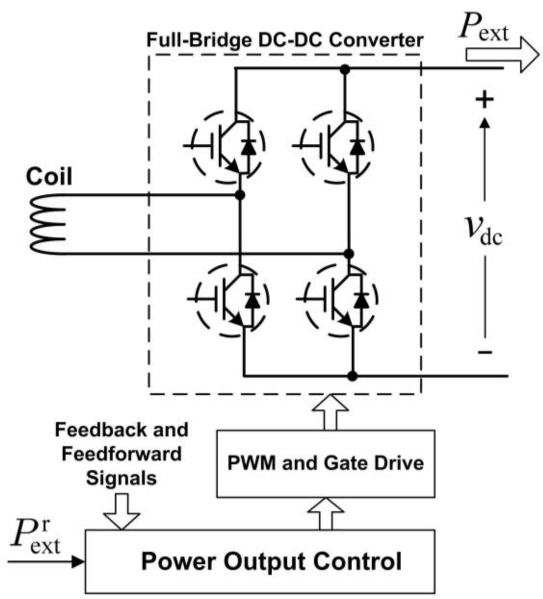

Figure 3. Schematic diagram of the conditioned energy resource for a SMES system

For the control, v_{dc}^{r} in Figure 1 is set to a fixed positive value, corresponding to the dc-link voltage control mode (Section 2), while $P_{\mathrm{ext}}^{\mathrm{r}}$ in Figure 3 is determined based on the charging/discharging requirements and the power deployment strategy; an auxiliary loop is required to override P_{ext}^{r} if the coil current exceeds its maximum permissible value when the coil is being charged.

3.6. Wind Energy Systems

Variable-speed wind energy systems represent another type of electronically interfaced DER systems that fit into the model of Figure 1. In a variable-speed wind energy system, a wind turbine drives a three-phase generator, either directly or through a gearbox. Then, the generator is interfaced with the host grid by an ac-dc-ac power-electronic converter. With reference to Figure 1 and Figure 2(b), one can consider the generator-side ac-dc converter to be the conditioning converter in the configuration of Figure 2(b), whereas the grid-side dc-ac converter is counted as a part of the power-electronic interface of Figure 1.

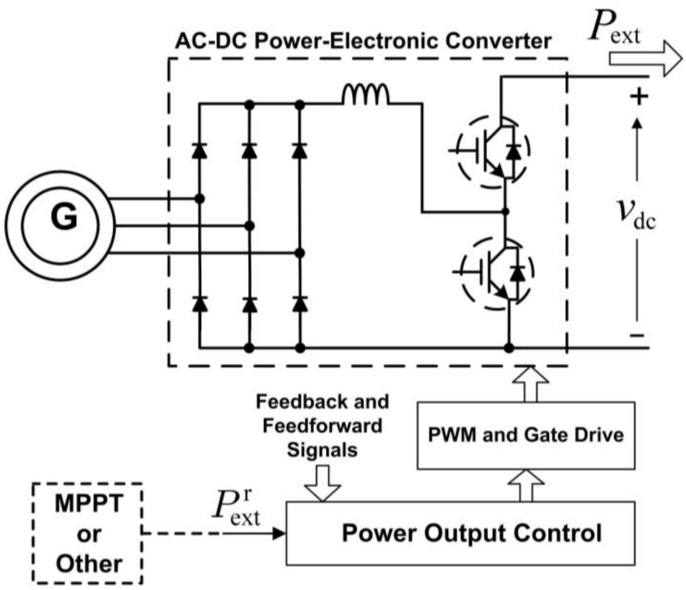

Figure 4. Schematic diagram of the conditioned energy resource for a small variable-speed wind energy system

To control the wind energy system, v_{dc}^{r} in Figure 1 is assigned a fixed positive value, corresponding to the dc-link voltage control mode (Section 2), while P_{ext}^{r} in Figure 2(b) is determined through an MPPT algorithm. More precisely, the main function of the generator-side converter is to control the generator torque. Therefore, the generator power is controlled by the torque and based on the speed of rotation. The net effect is that the control scheme of the generator-side converter can control the generator power and thus P_{ext}. Commonly, the MPPT algorithm determines the power setpoint, P_{ext}^{r}, based on the generator speed and the turbine power-speed characteristic. In a class of small variable-speed wind turbines, the conditioning converter consists of the back-to-back connection of a three-phase diode-bridge rectifier and a boost dc-dc converter (Carrasco et al, 2006), as shown in Figure 4 (the upper valve of the half-bridge leg only needs the diode, and the transistor may be omitted); depending on the power rating of the wind energy system, the inductor may be omitted from the rectifier dc side.

Wind energy systems using the doubly-fed induction generator (DFIG) represent a special case in relation to the models of Figure 1 and Figure 2(b). In a DFIG-based wind energy system, P_{ext} equals the power that leaves the rotor circuit of the generator, and the rest of the generator power flows from the stator circuit directly to the power system. The rotor power is, however, a small fraction of the total power, if the generator shaft speed is fairly close to the synchronous speed. Therefore, the power-electronic converters, Figure 1 and Figure 2(b), can have reduced power ratings.

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Biographical Sketch

Amirnaser Yazdani received the Ph.D. degree from University of Toronto, Toronto, ON, Canada, in 2005. From 2005 to 2006, he was with Digital Predictive Systems (DPS) Inc., Mississauga, Ontario, engaged in the design and simulation of high-power converters for variable-speed wind energy systems. From 2006 to 2011, he was an Assistant Professor with the University of Western Ontario, London, ON, Canada where he led a research team for modeling, analysis, and control design for electronically coupled distributed energy systems. Currently, he is an Associate Professor with Ryerson University, Toronto, ON, Canada. His research interests are in the areas of applications of power electronics in power systems, renewable energy systems, high-power electronic converters, and microgrids. Dr. Yazdani is an Associate Editor of the IEEE Transactions on Power Delivery, and also the Chairman of the IEEE Task Force on Modeling of Electronically-Interfaced Distributed Energy Resources (DERs). He is the coauthor of the book entitled “Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications”, John-Wiley/IEEE, 2009. He is a Professional Engineer of the Province of Ontario and an IEEE Senior Member.