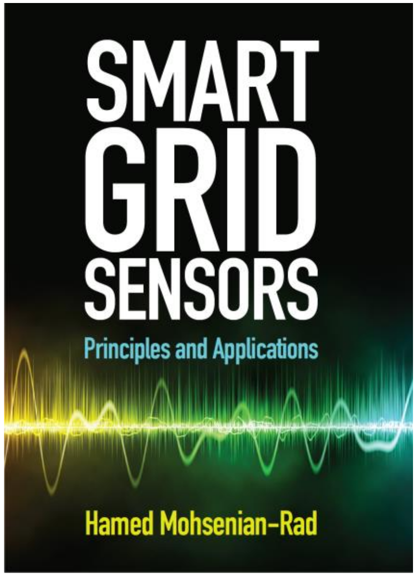
Chapter 6: Probing and Its Applications



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Overview

- Probing is the broad technique of *perturbing* the power system to enhance monitoring capabilities. Rather than only *passively* collecting measurements, probing methods use various grid components to *actively* create opportunities to learn about the power system and its unknowns.

- The perturbation that is needed in order to conduct probing can be created in different ways, such as by

    - load switching,
    - harmonic current injection, and
    - modulating power flow at power electronics devices.

- Probing could be a one-time action, or a sequence of actions.

    - The latter would create a *probing signal*.

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6.1. State and Parameter Estimation Using Probing

- We previously covered state and parameter in multiple chapters, such as in Section 3.8 in Chapter 3 and Section 5.8 in Chapter 5.

- So far, we have made the implicit assumption that the power system is observable; i.e., the available measurements are *sufficient* to allow obtaining the unknown states and/or unknown parameters.

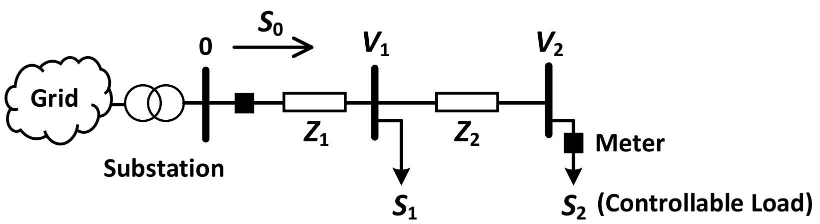
- In fact, it is often assumed that the available measurements *are more than sufficient*, i.e., they provide *redundancy*, such that we can even address error in measurements.

- Contrary to the above, in this section, we consider the cases where the available measurements cannot provide observability or redundancy.

- Probing actions may help in such circumstances.

6.1.1. Enhanced Observability

• Two meters are available in the network below to measure S_0 and S_2.



• There is no other sensor on this network.

• The load at bus 1 is *not* metered.

• The parameters of the load at bus 1 are *not* known either.

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- Based on the exponential load model in Section 5.7.1 in Chapter 5, the unknown load at bus 1 is modeled as follows:

$$S_1 = \left(\frac{|V_1|}{V_{1,\text{base}}} \right)^{\text{Re}\{\alpha\}} + j \left(\frac{|V_1|}{V_{1,\text{base}}} \right)^{\text{Im}\{\alpha\}}.$$

where $V_{1,\text{base}}$ and α are *not* known.

Overall, the unknowns include *both* load parameters and state variables:

$$V_{1,\text{base}}, \alpha, V_1, V_2.$$

The voltage at the substation is fixed at $V_0 = 1\angle 0^\circ$ p.u.

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- To estimate the unknowns in this system, we need to first formulate and then solve a system of equations based on the available measurements.

- From the Kirchhoff's Voltage Law (KVL) at each bus, we have:

$$
\begin{aligned}
V_1 &= V_0 - Z_1\left[\left(\frac{S_1}{V_1}\right)^* + \left(\frac{S_2}{V_2}\right)^*\right], \\
V_2 &= V_0 - Z_1\left[\left(\frac{S_1}{V_1}\right)^* + \left(\frac{S_2}{V_2}\right)^*\right] \\
&\quad - Z_2\left[\left(\frac{S_2}{V_2}\right)^*\right].
\end{aligned}
$$

6.1.1. Enhanced Observability

- Also, from the law of complex power conservation, we have:

$$
\begin{aligned}
S_0 = S_1 + S_2 \\
&+ Z_1 \left| \left(\frac{S_1}{V_1}\right)^* + \left(\frac{S_2}{V_2}\right)^* \right|^2 \\
&+ Z_2 \left| \left(\frac{S_2}{V_2}\right)^* \right|^2,
\end{aligned}
$$

where the second line indicates the power losses on distribution lines.

The operator $\{\cdot\}*$ denotes conjugate transpose.

The impedance on each distribution line is assumed to be known.

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- Suppose, we have (all in per unit):

$$Z_1 = 0.000059292 + j0.000030225,$$
$$Z_2 = 0.000317040 + j0.000161478.$$

- Once we replace S_1 with its expression from Slide 7, the system of equations in Slides 8 and 9 would provide us with three independent equations; which are sufficient to obtain *three* independent unknowns.

- However, the number of independent unknowns is *four*, see Slide 7.

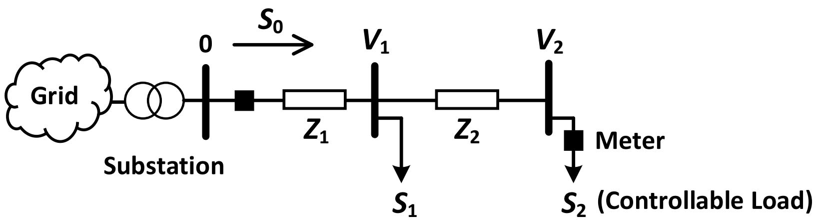
- Therefore, this power system is *under-determined* and *unobservable*.

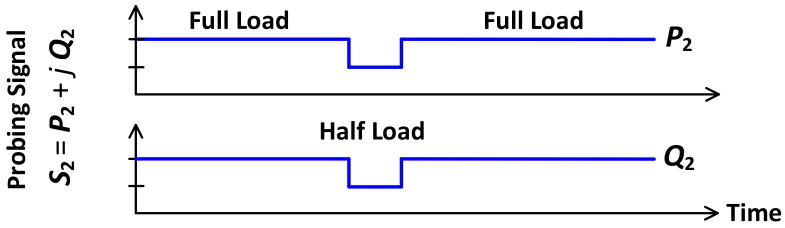
6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

Probing can help achieve observability in the system in this example.

Suppose we can control the load at bus 2 and we momentarily cut it by half, such as for one second. This can create a *probing signal* at bus 2.





6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

The measurements that are collected in the system during this momentary probing action provide us with additional information about the understudy power system that can help us make the system observable.

During *full load* operation, we collect the following measurements:

$$S_0^{\text{full}}, S_2^{\text{full}}.$$

The unknowns in the system during *full load* operation are:

$$V_{1,\text{base}}, \alpha, V_1^{\text{full}}, V_2^{\text{full}}.$$

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

Similarly, during *half load* operation, we do the following measurements:

$$S_0^{\text{half}}, S_2^{\text{half}}.$$

The unknowns in the system during *half load* operation are:

$$V_{1,\,\text{base}}, \alpha, V_1^{\text{half}}, V_2^{\text{half}}.$$

The system of equations in Slides 8 and 9 holds during both full load and half load operation. It holds over the measurements and unknowns on Slide 12 as well as the measurements and unknowns on Slide 13.

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

Key Assumption: Since the probing action is done over a short period of time, the two unknown parameters of the load at bus 1, i.e., $V_{1,\text{base}}$ and α, can be reasonably assumed to stay unchanged during the probing action.

Accordingly, we now have an *equal number* of unknowns and equations. We have six unknowns and six independent equations, which include the equations during full load operation and those during half load operation.

The system is now observable.

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

- **Example 6.1**: Consider the power system and the momentary probing action that we discussed on Slide 11. The measurements are:

$$
\begin{aligned}
S_0^{\text{full}} &= 3.539551 + j1.629843 \\
S_2^{\text{full}} &= 1 + j0.25 \\
S_0^{\text{half}} &= 2.287646 + j1.328913 \\
S_2^{\text{half}} &= 0.5 + j0.125.
\end{aligned}
$$

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

- **Example 6.1 (Cont.)**: The unknowns in this system are obtained as

$$V_{1,\text{base}} = 0.980$$
$$\alpha = 1.808 + j1.401$$

and

$$V_1^{\text{full}} = 0.999741\angle{-0.000593^\circ}$$
$$V_2^{\text{full}} = 0.998850\angle{-0.012841^\circ}$$
$$V_1^{\text{half}} = 0.999824\angle 0.000553^\circ$$
$$V_2^{\text{half}} = 0.999379\angle{-0.005568^\circ}.$$

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

- **Example 6.1 (Cont.)**: Thus, with the assistance of probing, we are able to estimate not only the unknown load parameters but also the unknown state variables of the power systems under both full loading and half loading conditions of the controllable load at bus 2.

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- **Achieving Observability with Probing Action**:

- Note that probing may *not* always resolve the lack of observability.

- For example, suppose we extend the distribution feeder on Slide 6 to include one more bus; without adding any additional meter.

- In that case, the parameters and the states at the new bus would remain unobservable, no matter what probing signal we use at bus 2.

- The conditions under which probing can enhance observability in power distribution systems are discussed in [176, 396, 397].

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

• **Probing in Practice:** Probing action is meant to be done over a short period of time, because we want all the parameters in the system to remain constant, except for the probing parameter.

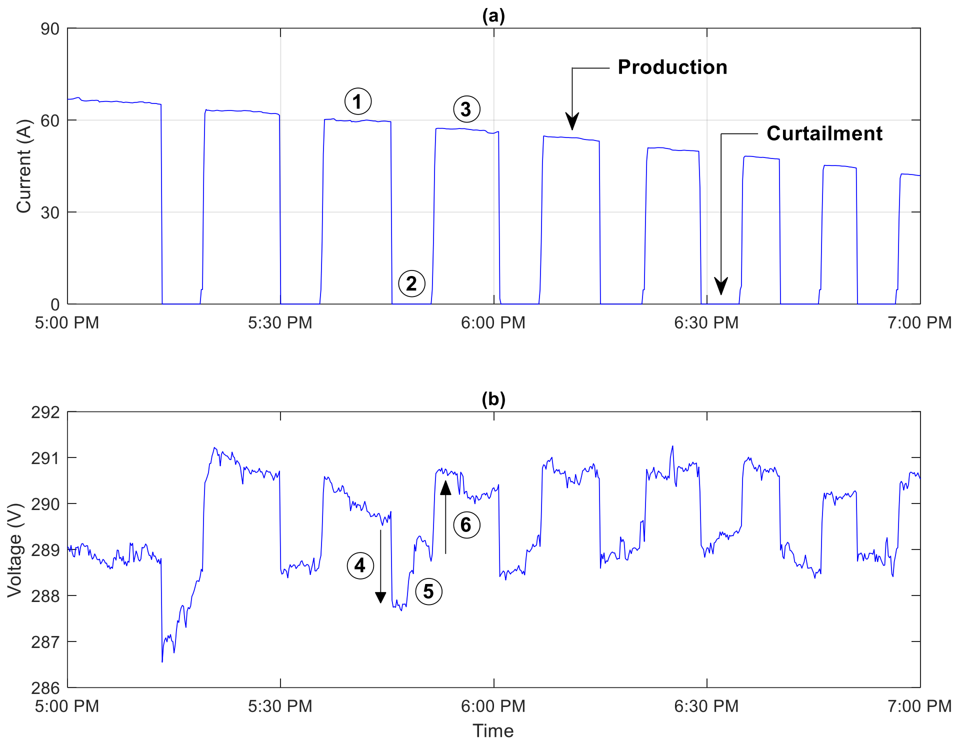
However, in practice, what we measure during a probing action includes also the impact of the ongoing changes in the system.

Thus, the measurements should be examined to remove the impact of such unintended changes in the system.

It is helpful if we can *repeat* the probing actions to better capture the changes in the system that are directly the result of probing actions.

6.1.1. Enhanced Observability

- **Example 6.2:** Figure below shows the results of several back-to-back probing actions that are done in a 90 kW PV inverter.



6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- **Example 6.2 (Cont.):** The probing actions are done on a summer day over a period of two hours from 5 PM till 7 PM; i.e., during a period when the production is gradually declining in the evening.

- As shown in the top figure on Slide 20, the probing parameter is the generation output of the PV inverter, which is switched between full production, as in Point ①, and full curtailment, as in Point ②, and then it goes back to full production, as in Point ③.

- The corresponding *impact* of the probing actions on the voltage at the point of the PV inverter's interconnection with the power grid is shown in the bottom figure on Slide 20.

6.1. State and Parameter Estimation Using Probing

6.1.1. Enhanced Observability

- **Example 6.2 (Cont.):** We can see that the sudden curtailment from ① to ② results in a sudden decrease in voltage, as marked by ④.

- The subsequent changes in voltage over the next few minutes, which are marked by ⑤, are not due to the probing action.

- The next impact of probing is in the sudden increase in voltage, as marked by ⑥, which is due to the sudden return to full production from ① to ②. Therefore, we must focus only on the changes at ④ and ⑥ as the direct impact of the probing action in our analysis.

- Of course, since the probing actions are repeated in this example, we can better estimate how much the voltage is impacted per each 1 A change in the current that is injected by the PV unit to the power grid.

6.1.2. Enhanced Redundancy

- Even when the power system is already observable, probing may help by creating additional redundancy in measurements to enhance accuracy in the presence of measurement error.

- For instance, in Example 6.1, suppose we *do* know $V_{1,\text{base}}$. That is, suppose, the only unknown load parameter would be α.

- In that case, since $V_{1,\text{base}}$ is no longer unknown, the number of independent unknowns reduces from four to three. Thus, the number of unknowns becomes equal to the number of independent equations.

    - The power system becomes observable even without probing.

6.1.2. Enhanced Redundancy

• Nevertheless, if we use probing, we can enhance the accuracy in estimating the remaining unknown load parameter α.

• Specifically, if we use probing in this scenario, then the number of independent unknowns would be five, as listed below:

$$\alpha, V_1^{\text{full}}, V_2^{\text{full}}, V_1^{\text{half}}, V_2^{\text{half}}.$$

• Yet, the number of equations remains at six. This creates redundancy in our analysis. An example is given in Exercise 6.2; also see [176, 396].

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6.2. Topology and Phase Identification Using Probing

- Probing can help with topology identification in different ways.

- First, recall from Section 3.8.3 in Chapter 3 that topology identification can be formulated as a parameter estimation problem, where the unknown parameters are the status (open or closed) of the switches.

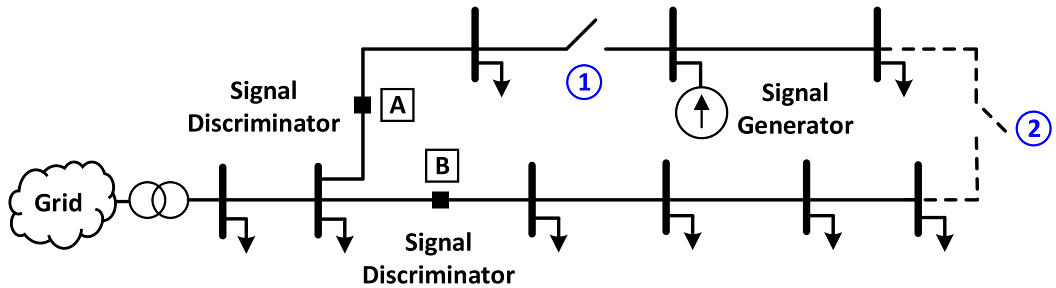
    - Accordingly, probing can help by enhancing observability or redundancy in the topology identification problem, based on the same principles that we discussed in Section 6.1.

- Second, probing can help with topology identification also by using a group of signal generators and signal discriminators.

- For the rest of this section, our focus will be on the second possibility.

6.2.1. Topology Identification

• Consider a power distribution system with two switches, ① and ②:

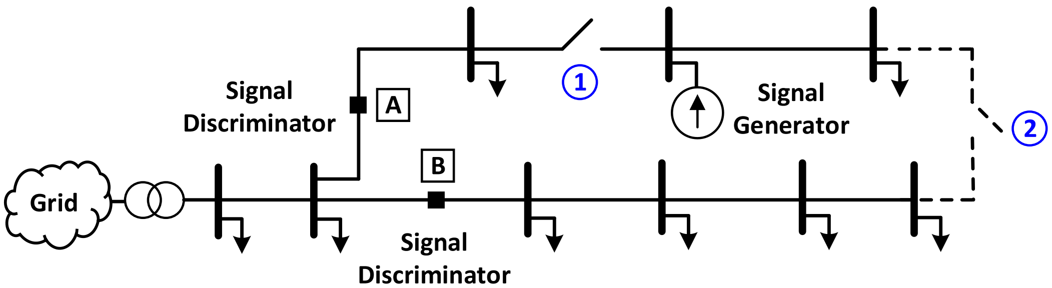


• One signal generator and two signal discriminators are installed.

• The *signal generator* (such as a *harmonic current source*) is the probing device to generate a current signal that can be distinguished from the fundamental power signal or any other source in the network.

6.2.1. Topology Identification

• Consider a power distribution system with two switches, ① and ② :



• The two *signal discriminators* that are denoted by letters A and B.

• They can be any current sensor that is capable of detecting the signal that is generated by the signal generator. For example, depending on the choice of the probing signal, the signal discriminators can be power quality meters, waveform sensors, H-PMUs, etc.; see Chapter 4.

6.2. Topology and Phase Identification Using Probing

6.2.1. Topology Identification

• Recall from the analysis in Section 4.5.2 that the harmonic current *flows almost entirely through the substation* and not through the loads.

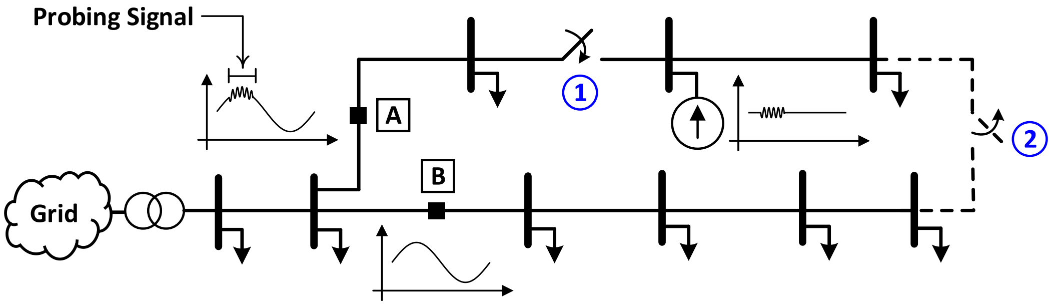
• Therefore, one can identify the network topology by checking whether any of the signal discriminators can detect the probing signal.

• Two examples are illustrated in the next two slides.

6.2. Topology and Phase Identification Using Probing

6.2.1. Topology Identification

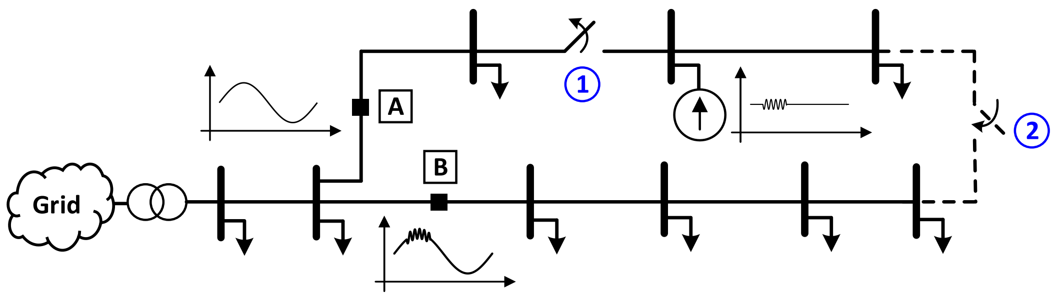
- If switch ① is *closed* and switch ② is *open*, then the harmonic current flows through the substation, the probing signal that is generated by the signal generator flows through switch ①. As a result, the probing signal is detected by signal discriminator A and *not* by signal discriminator B.



6.2. Topology and Phase Identification Using Probing

6.2.1. Topology Identification

- If switch ① is *open* and switch ② is *closed*, then the harmonic current flows through the substation, the probing signal that is generated by the signal generator flows through switch ②. As a result, the probing signal is detected by signal discriminator B and *not* by signal discriminator A.



6.2.1. Topology Identification

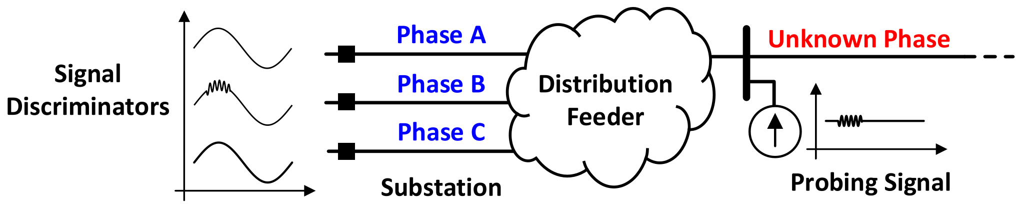
• By comparing the results in Slide 31 with those in Slide 32, we can conclude that the network topology can be identified based on whether each of the signal discriminators can detect the probing signal.

• Note: The above analysis is applicable only to a *radial* network, where there is only one path from the signal generator to the substation.

• For a larger radial network with multiple laterals and several switches, one may need to install *multiple* signal generators to fully identify the network topology. The signal generators should generate distinct signals. For example, they may have to inject harmonic currents at frequencies that are different from each other; e.g., see the analysis in [252].

6.2.2. Phase Identification

• The probing in Section 6.2.1 can also be used for phase identification.



• The single-phase bus on the right-hand side has an unknown phase. A signal generator is installed at this bus to generate a probing signal.

• On the left-hand side, there are three phases, labeled as A, B, and C. Each phase has a signal discriminator. The probing signal is detected by the signal discriminator at bus B. Thus, the unknown phase is Phase B.

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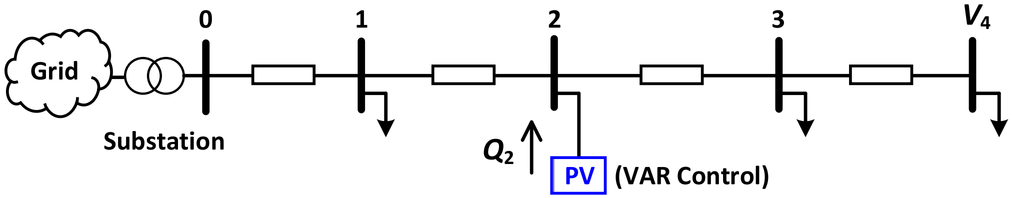
6.3. Model-Free Control Using Probing

- It is common for smart grid control applications to use the measurements together with a *model* of the power system.

- However, what if such a model is not available?

- A probing action may help in such cases.

- Consider a basic Volt/VAR Control (VVC) problem in a power distribution system. The objective is to control reactive power injection at the PV inverter at bus 2 to regulate voltage at the end of the feeder at bus 4.



6.3. Model-Free Control Using Probing

- Suppose the model of the system is not available. However, we are able to measure *reactive power injection* at bus 2 and also *voltage magnitude* at bus 4. These quantities are denoted by Q_2 and V_4, respectively.

- To conduct VVC, we need to know the *relationship between Q_2 and V_4*.

- That is, we need to know function f (·) in the following expression:

$$V_4 = f(Q_2).$$

- The above function can be obtained if the system model is available and all the loads also are measured and known. However, if such information is not available, then we can still estimate f (·) using a probing action.

6.3. Model-Free Control Using Probing

- First, consider the normal operation of the PV inverter. The following relationship holds between the two quantities that are being measured:

$$V_4^{\text{normal}} = f(Q_2^{\text{normal}}).$$

- Next, suppose the PV inverter perturbs its reactive power injection:

$$Q_2^{\text{perturbed}} = Q_2^{\text{normal}} + \Delta Q,$$

where ΔQ denotes the amount of perturbation. The following relationship must hold between the available measurements during the perturbation:

$$V_4^{\text{perturbed}} = f(Q_2^{\text{perturbed}}).$$

6.3. Model-Free Control Using Probing

- Assuming that the perturbation is small, we can obtain a *first-order approximation* for the unknown relationship between the quantities as:

$$f(Q_2) \approx f(Q_2^{\text{normal}}) + \frac{f(Q_2^{\text{perturbed}}) - f(Q_2^{\text{normal}})}{Q_2^{\text{perturbed}} - Q_2^{\text{normal}}}(Q_2 - Q_2^{\text{normal}}).$$

- Therefore, we can approximate the relationship between Q_2 and V_4 as

$$V_4 \approx V_2^{\text{normal}} + \frac{V_2^{\text{perturbed}} - V_2^{\text{normal}}}{Q_2^{\text{perturbed}} - Q_2^{\text{normal}}}(Q_2 - Q_2^{\text{normal}}).$$

- Here, the perturbation in reactive power injection serves as a probing action to help us address the lack of access to a system model.

6.3. Model-Free Control Using Probing

- **Example 6.3**: Again, consider the distribution system on Slide 37. Even though the network topology is known; the line impedances and the loads are unknown. Thus, the system model overall is unknown.

Suppose the measurements are

$$Q_2^{\text{normal}} = 10, \qquad V_4^{\text{normal}} = 0.989849,$$
$$Q_2^{\text{perturbed}} = 30, \qquad V_4^{\text{perturbed}} = 0.989888.$$

All the quantities are in per unit. From Slide 40, the relationship between reactive power injection at bus 2 and the voltage at bus 4 is obtained as

$$V_4 \approx 0.989849 + 1.95 \times 10^{-6}\,(Q_2 - 10).$$

6.3. Model-Free Control Using Probing

- **Example 6.3 (Cont.)**: We can use the model from Slide 41 to choose the amount of reactive power injection by the PV inverter in order to regulate voltage V_4. For instance, suppose we seek to increase V_4 to 0.99 p.u. The PV inverter must set its reactive power injection at

$$Q_4 = 10 + (0.99 - 0.989849) \,/\, 1.95 \times 10^{-6} \approx 87.4 \text{ p.u.}$$

6.3. Model-Free Control Using Probing

- Probing can be used similarly to support model-free control in other smart grid applications, such as in power flow control; see Exercise 6.8.

- Important advancements have been reported in recent years to use probing in *model-free optimal control* in smart grid control applications.

- For example, in [399], probing is used at a PV inverter to learn the *gradient* of the objective function in a model-free power loss minimization problem in a power distribution system.

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6.4. Modal Analysis with Probing

- Recall from Section 2.6.3 in Chapter 2 that the electromechanical modes of the power system can be estimated by applying modal analysis to various power system measurements during *transient oscillations*.

- However, our ability to conduct modal analysis depends on how significant the magnitude of the oscillations are compared to ambient noise, and also how often a significant transient oscillatory event occurs.

- Accuracy and repeatability in estimating the electromechanical modes of the power system can be improved by using probing signals.

    - In this approach, instead of relying on random natural events to occasionally excite the electromechanical modes of the power system, *these modes are excited by injecting a probing signal*.

6.4. Modal Analysis with Probing

6.4.1. Probing with Resistive Brake

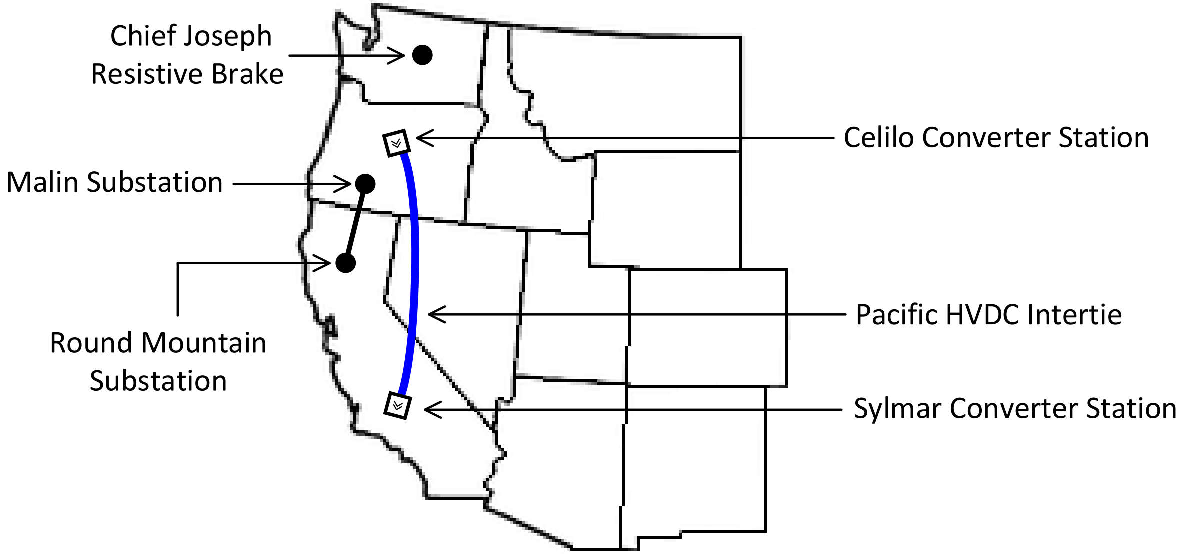
- A resistive brake is used in power systems to quickly dissipate a large amount of energy. Brakes are often primarily designed to enhance transient stability in power systems during a fault contingency.

- However, they can also be used to excite the power system when needed in order to conduct modal analysis.

6.4. Modal Analysis with Probing

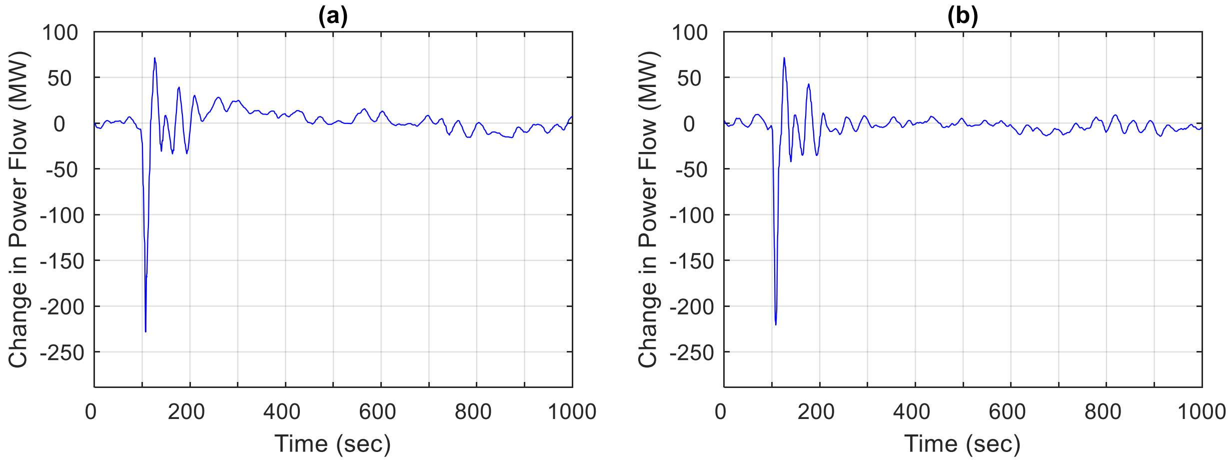
6.4.1. Probing with Resistive Brake

• The resistor brake at Chief Joseph substation is designed to dissipate 1400 MW of power when energized at 240 kV. It withstands operation for up to three seconds before it is de-energized for cooling [400].



6.4.1. Probing with Resistive Brake

• **Example 6.4:** Figure below shows power system measurements at Malin substation during *two brake insertion events*. The second brake insertion occurred only five minutes after the first brake insertion.



6.4. Modal Analysis with Probing

6.4.1. Probing with Resistive Brake

• During the *first brake insertion*, the change in the power flow on the transmission line between the Malin substation and the Round Mountain substation is as shown in Figure (a) on Slide 49.

• During the *second brake insertion*, the change in the power flow on the transmission line between the Malin substation and the Round Mountain substation is as shown in Figure (b) on Slide 49.

• We can see that the system excitation was *repeatable*, and the resulting oscillations are similar in the two experiments.

6.4. Modal Analysis with Probing

6.4.2. Probing with Intermittent Wave Modulation

- The fact that probing is repeatable allows *creating redundancy* in estimating the electromechanical modes of the power system.

- The dominant modes during the *first brake insertion* are obtained as:

$$0.241 \text{ Hz with } 12.4\% \text{ Damping}, \quad 0.379 \text{ Hz with } 8.5\% \text{ Damping}.$$

- The dominant modes during the *second brake insertion* are obtained as:

$$0.244 \text{ Hz with } 10.7\% \text{ Damping}, \quad 0.360 \text{ Hz with } 9.1\% \text{ Damping}.$$

- Having multiple estimations can help improve the accuracy in estimating the electromechanical modes of the system. For instance, we can take the average of the results or apply other statistical analysis to the results.

6.4. Modal Analysis with Probing

6.4.2. Probing with Intermittent Wave Modulation

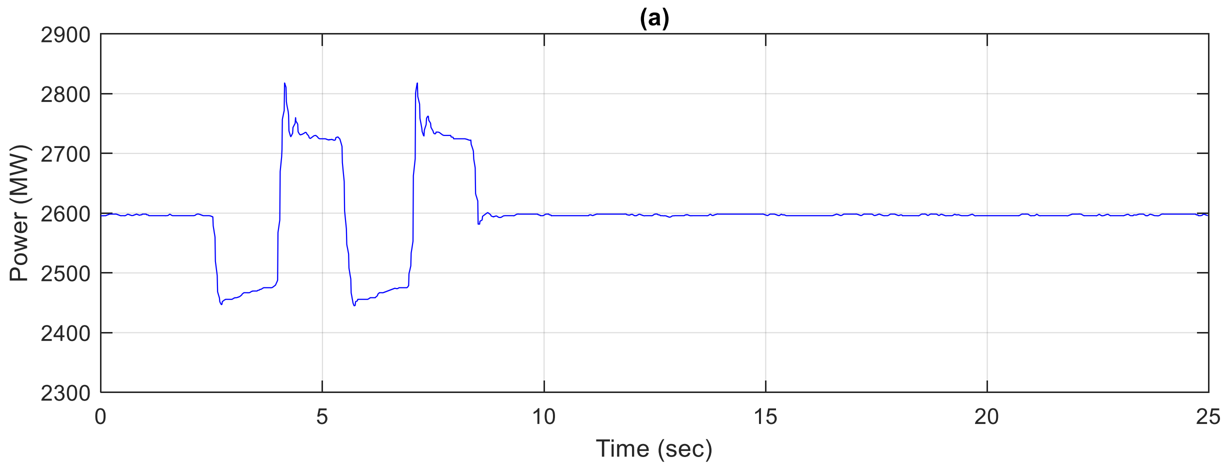
- Probing in modal analysis can also be done by *modulating a probing waveform* on an High Voltage DC (HVDC) lines using power electronics.

- For example, for Pacific HVDC Intertie on the Western Interconnection, Celilo Converter Station in the state of Oregon is at the northern terminus of the intertie, and Sylmar Converter Station in Southern California is at the southern terminus of the intertie; see the map on Slide 48.

6.4. Modal Analysis with Probing

6.4.2. Probing with Intermittent Wave Modulation

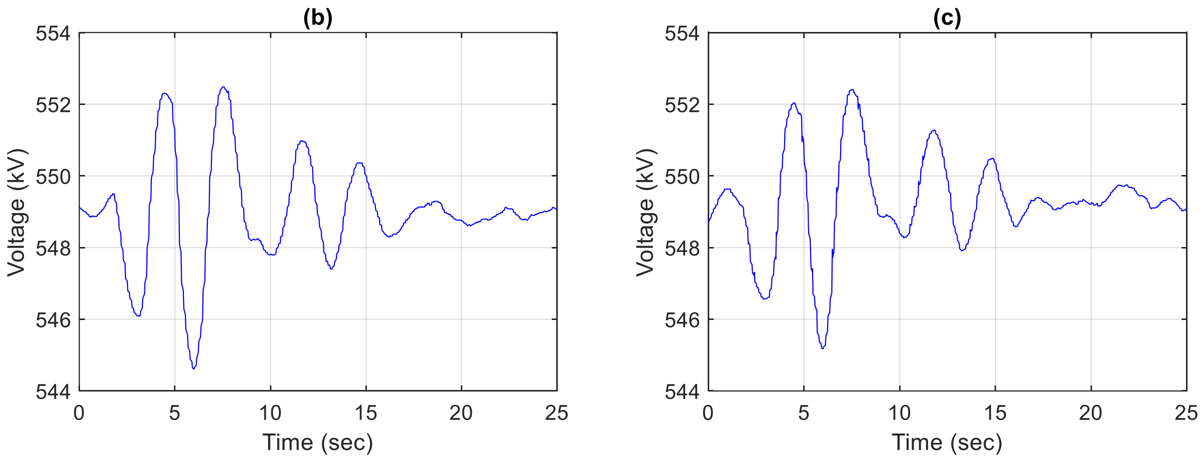
- **Example 6.5**: Figure (a) shows a probing wave during a modal analysis experiment at the Pacific HVDC Intertie (Western Interconnection). The power electronics converters modulated two cycles of a ±125 MW square wave on the DC transmission line. The experiment was done twice [402].



6.4. Modal Analysis with Probing

6.4.2. Probing with Intermittent Wave Modulation

- **Example 6.5 (Cont.)**: The measured voltages at the Malin substation during the two experiments are shown in Figures (b) and (c), respectively.



6.4.2. Probing with Intermittent Wave Modulation

• **Example 6.5 (Cont.)**: The dominant modes of the system during the first experiment are estimated as [402]:

$$0.303 \text{ Hz with } 10.2\% \text{ Damping}, \quad 0.416 \text{ Hz with } 9.0\% \text{ Damping}.$$

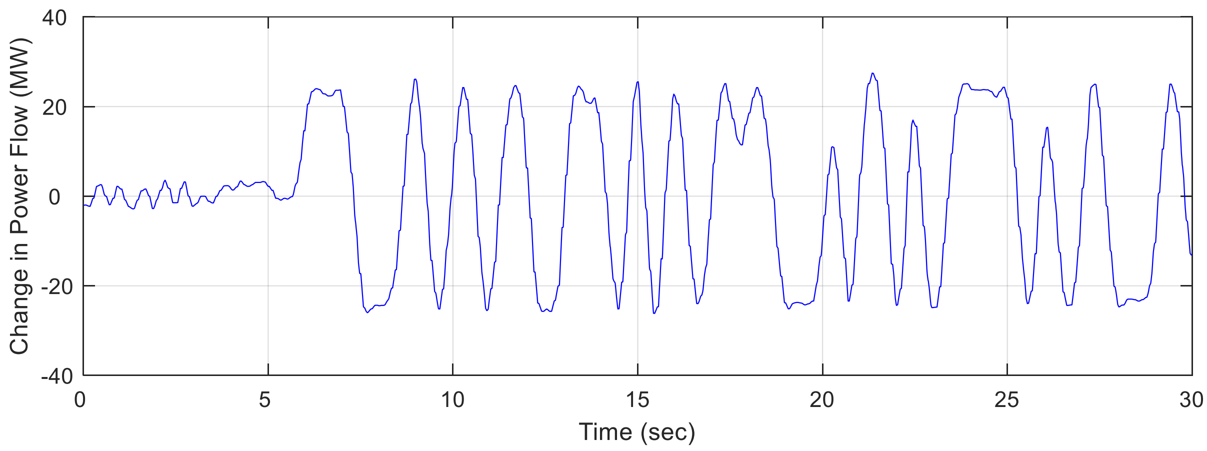
The dominant modes during the second experiment are estimated as

$$0.296 \text{ Hz with } 10.0\% \text{ Damping}, \quad 0.416 \text{ Hz with } 8.0\% \text{ Damping}.$$

We can see that the probing experiment was repeatable and provided redundancy in estimating the electromechanical modes of the system.

6.4.2. Probing with Intermittent Wave Modulation

• More complex probing signals may also be used for the purpose of modal analysis. For example, figure below shows a longer *±25MW noise wave* that has been modulated on the Pacific HVDC Intertie.

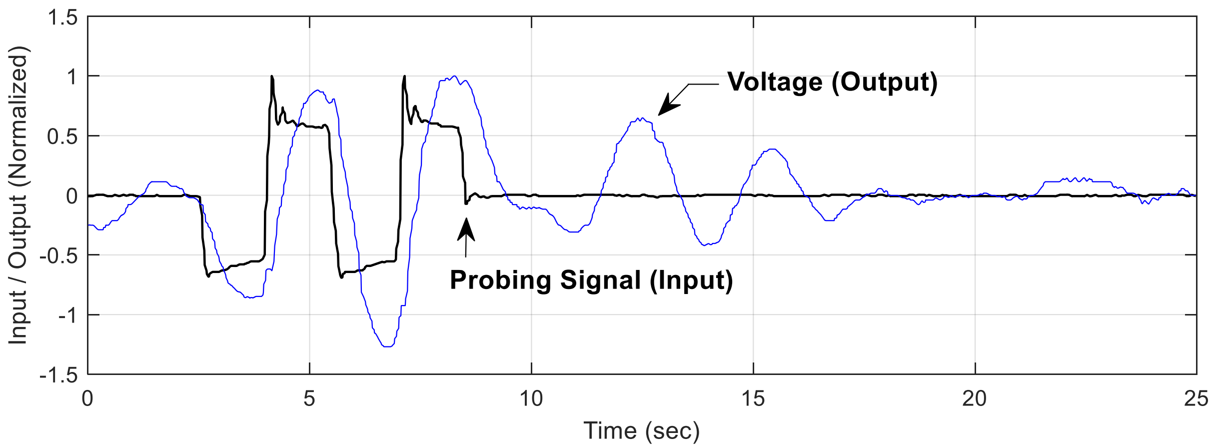


• This type of noise modulation probing signals can excite the power system across a range of local oscillation modes. The above probing signal in can *excite the system at frequencies from 0.1 Hz to 1.1 Hz*; see [403].

6.4.3. Input–Output System Identification

- With known input signals, one can seek to also obtain an *input–output model* for the power system. Here, the input to the system is the probing signal, and the output from the system is the measurement.

- The input-output relationship in Example 6.5 is shown below.



6.4. Modal Analysis with Probing

6.4.3. Input–Output System Identification

- A simple input–output model that can be considered is the discrete linear Auto-Regressive eXogenous (ARX) model. It can be formulated as:

$$x(m) = a_1 x(m-1) + a_2 x(m-2) + \cdots + a_m x(0)$$
$$+ b_1 u(m-1) + b_2 u(m-2) + \cdots + b_p u(m-p),$$

where p ≤ m. Here, power system measurement $x(t)$ at time sample m is approximated based on its previous samples and also the previous samples of the probing signal $u(t)$, which is an input to the system.

The above ARX model is an extension of the AR model in Chapter 2.

Input–output system identification is beyond the scope of this book. A good classic textbook on system identification is [404].

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6.5. Power Line Communications as a Probing Tool

• Power line communications (PLC) is a *wired* (as opposed to *wireless*) communication technology that reuses power lines as the media for the purpose of data transmission (in addition to power transmission).

• PLC superimposes a high-frequency communication signal over the 60 Hz (or 50 Hz) electrical signal in an existing power cable.

• The fact that PLC signals travel through power lines makes reliable communication challenging. However, it also provides us with a distinct advantage that is of interest in this book: By observing the PLC signal that is sent through the grid, we can learn about the status of the power grid itself, such as to diagnose incipient faults in power cables or to identify the grid topology. This is a unique property of PLC, because PLC is the only "*through the grid*" communications technology in smart grids [410].

6.5. Power Line Communications as a Probing Tool

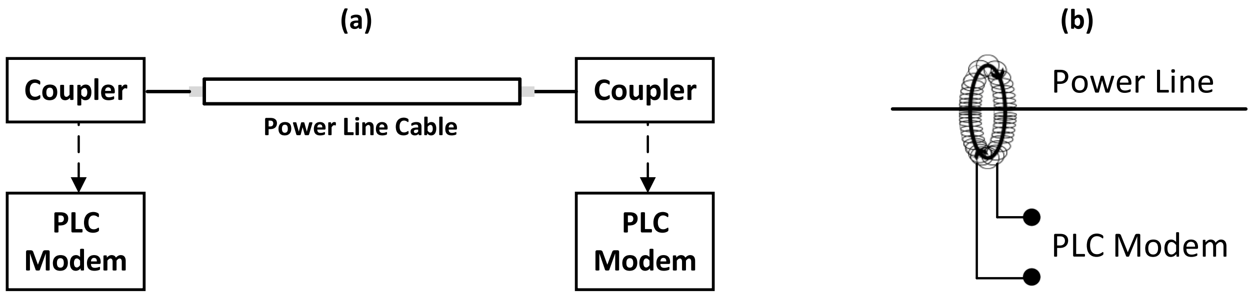
- In principle, monitoring power grid using PLC is a probing method.

- However, unlike most other probing methods, power grid monitoring via PLC does *not* entail any additional equipment installation, as long as the PLC system is already deployed as the choice for communications.

6.5. Power Line Communications as a Probing Tool

6.5.1. Basics of Power Line Communications

- The basic architecture for power line communications:

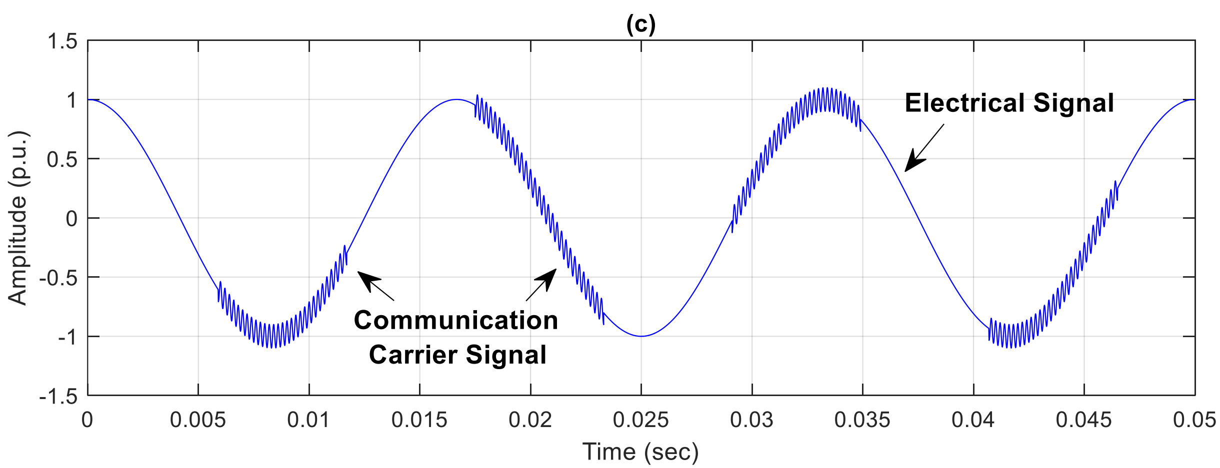


- At the transmitter, data is first modulated into a communication carrier signal by the modem. The *communication carrier signal* is then injected into the power line by a coupling device that acts as a PLC modem. At the receiver, the communication carrier signal is extracted from the power line by another coupling device that too acts as a PLC modem. The signal is then demodulated by the modem to obtain the original data.

6.5.1. Basics of Power Line Communications

- A survey of coupling technologies for PLC is available in [411].

- Once the modulated high-frequency communication carrier signal is *superimposed* to the power cable, the resulting voltage or current waveform will be conceptually similar to the figure below.



6.5. Power Line Communications as a Probing Tool

6.5.1. Basics of Power Line Communications

- The frequency of the communication carrier signal depends on the PLC technology being used and the communication standard.

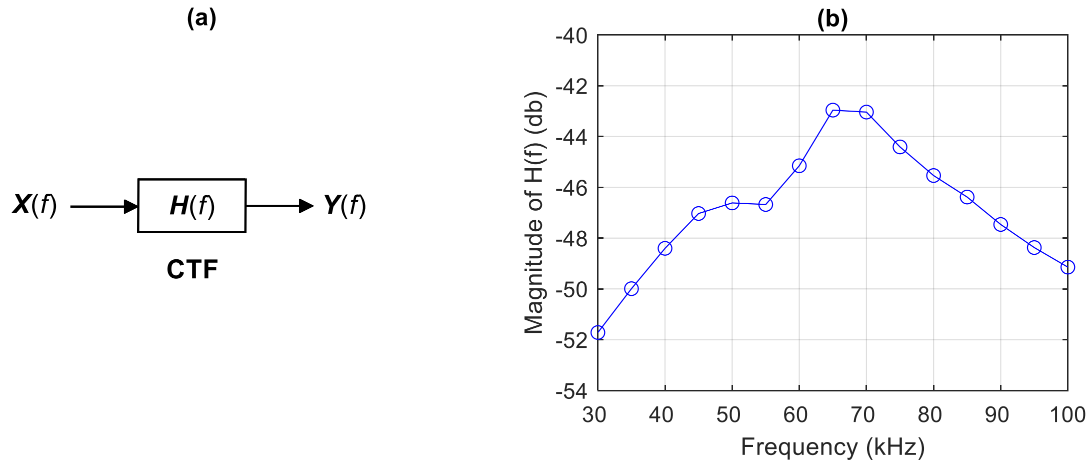
- For example, in the United States, the Federal Communications Commission (FCC) allows frequencies of 10–490 kHz for narrow-band PLC (NB-PLC). Most existing NB-PLC technologies use Orthogonal Frequency-Division Multiplexing (OFDM) as the modulation method.

- To support smart grid applications, we often need a network of PLC devices. They communicate with each other directly, when they are within the communication range of each other. Otherwise, they communicate via PLC relays. PLC relays may also be needed at a location with step-change transformers; see [413] for more details.

6.5.2. Signal Attenuation and Channel Estimation

• Transmitted PLC signals experience attenuation, i.e., they lose strength, as they travel through the power line. Attenuation is affected by several factors, such as the length and the type of the conductor.

• The extent of attenuation depends on the *frequency* of the signal. This is modeled by the *channel transfer function* (CTF), denoted by *H*(*f*):



6.5.2. Signal Attenuation and Channel Estimation

• CTF is the Fourier transformation of the channel impulse response.

• Notations $X(f)$ and $Y(f)$ on the previous slide denote the transmitted communication signal and the received communication signal, both in frequency domain. From the definition of CTF, at any frequency f, we have

$$Y(f) = H(f)\, X(f).$$

• The magnitude of $H(f)$ for a real-world NB-PLC channel is shown in Figure (b) on the previous slide. At $f = 70$ kHz, the magnitude of $H(f)$ is −43 dB, i.e., the communication signal has only about 0.7% of its original strength.

6.5. Power Line Communications as a Probing Tool

6.5.2. Signal Attenuation and Channel Estimation

• We can see that the attenuation level varies significantly across the examined frequency band. CTF often fluctuates over day and night due to various reasons. Therefore, most PLC protocols perform channel estimation when they need to transmit new data.

• For example, they may perform the following steps:

- Idle Channel: to measure noise levels;
- Transmit Test Sequence: to estimate the channel transfer function;
- Transmit Data: to transfer the actual data.

• The results from channel estimation are used by digital signal processing algorithms in PLC devices to improve the accuracy of data transfer.

6.5. Power Line Communications as a Probing Tool

6.5.2. Signal Attenuation and Channel Estimation

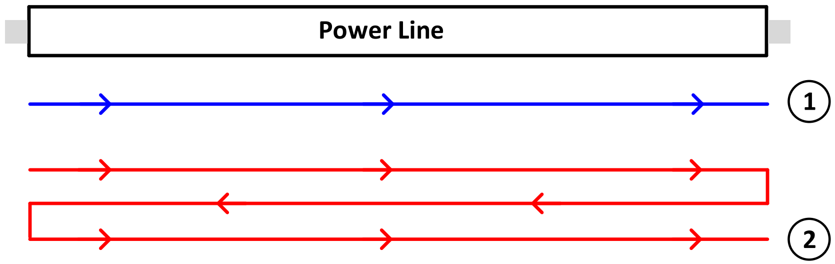
- Another physical phenomenon in PLC systems is the reflection of the communication signal at locations with impedance mismatch.

- That is, there is an “echo” of the transmitted communication signal at any point where there is a change in impedance.

- At the very least, reflection occurs at the receiver and also subsequently at the transmitter, as shown in the Figure on the next page.

6.5.3. Signal Reflection at Impedance Discontinuities

• Signal ① is the communication signal that is received at the receiver through the direct path. Signal ② is a reflected signal that was first echoed at the receiver and then echoed also at the transmitter.



• Additional reflected signals arrive at the receiver, after four echos, six echos, and so on, although they are not shown in this figure. Reflected signals are attenuated more than the original signal because they travel longer through the power cable. Nevertheless, their impact must be addressed by using proper signal processing methods; cf. [412].

6.5.4. Applications to Power System Monitoring

- Both signal attenuation and signal reflection can be studied as underlying principles to conduct certain power system monitoring tasks.

- Next, we will discuss two common applications in Sections 6.6 and 6.7.

- Additional discussions on the applications of PLC in power system monitoring are available in [410, 415–426].

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6.6. Fault Location Identification Using PLC

- PLC can help detect and identify the location of a fault in a power line.

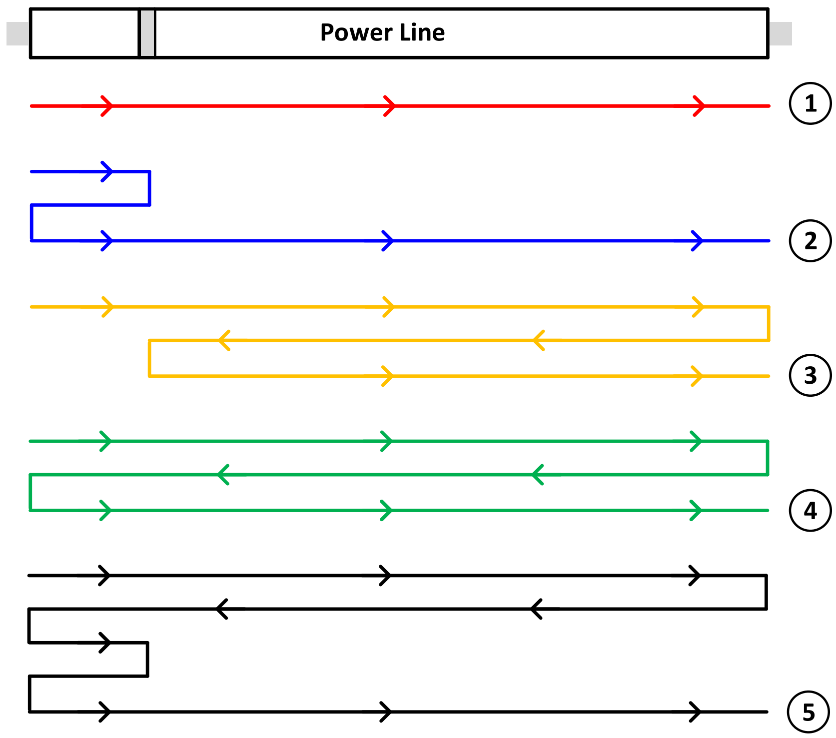
- One idea is to utilize the fact that damage in a cable causes a change in impedance of the cable at the location of the damage.

- From Section 6.5.3, we know that a change in impedance causes reflection in the communication signal:

  - **Healthy cable**: reflections occur only at the receiver and the transmitter.

  - **Damaged cable**: reflections occur also at the point of damage. Thus, the location of the fault can be estimated by investigating the characteristics of the reflected signal.

- **Example 6.6**: Consider a PLC system over a L = 1000 m power cable. The cable is partly damaged at a location that is l = 150 m away from the PLC transmitter. Due to the mismatch in impedance, the communication waves reflect when they reach the location of the cable that is damaged.



6.6. Fault Location Identification Using PLC

- **Example 6.6 (Cont.)**: In the figure on the previous slide, Signal ① is the communication signal that is received at the receiver through the direct path. Signal ② is a reflected signal that is first echoed at the damaged location and then subsequently also echoed at the transmitter. Signal ③ is a reflected signal that is first echoed at the receiver and then subsequently also echoed at the damaged location. Signals ④ and ⑤ can be explained similarly. Other reflected signals are also created and ultimately arrived at the receiver, which are not shown here; cf. [427].

6.6. Fault Location Identification Using PLC

- By can detect and identify the location of the damage on the power line by comparing the following two scenarios:

  - the figure on Slide 70 for a healthy cable
  - the figure on Slide 75 for a damaged cable

- The damage in a cable causes a *change in impedance* of the cable at the location of the damage. From Section 6.5.3, we know that a change in impedance causes *reflection* in the communication signal.

- In a healthy cable, reflections occur only at the receiver and the transmitter (as in Slide 70). In a damaged cable, reflections occur also at the point of damage (as in Slide 75). Thus, the location of the fault can be estimated by *investigating the characteristics of the reflected signal*.

6.6. Fault Location Identification Using PLC

- Recall from Section 6.5.1 that the PLC modems frequently estimate $H(f)$.

- $H(f)$ in a cable that has a damage at an unknown location can be written as a product of the channel transfer function $H_{\text{healthy}}(f)$ of the healthy cable, and the channel transfer function $H_{\text{dmg}}(f)$ of the damaged cable:

$$H(f) = H_{\text{healthy}}(f)\, H_{\text{dmg}}(f).$$

- In practice, one can assume that $H_{\text{healthy}}(f) \approx H(f)$ at the time of installing the PLC modems. In other words, one can assume that the cable was initially healthy at the time that the PLC modems were first installed.

6.6. Fault Location Identification Using PLC

- From the equation on the previous slide, and based on the historical estimation of $H_{\text{healthy}}(f)$ prior to the cable damage, we can obtain:

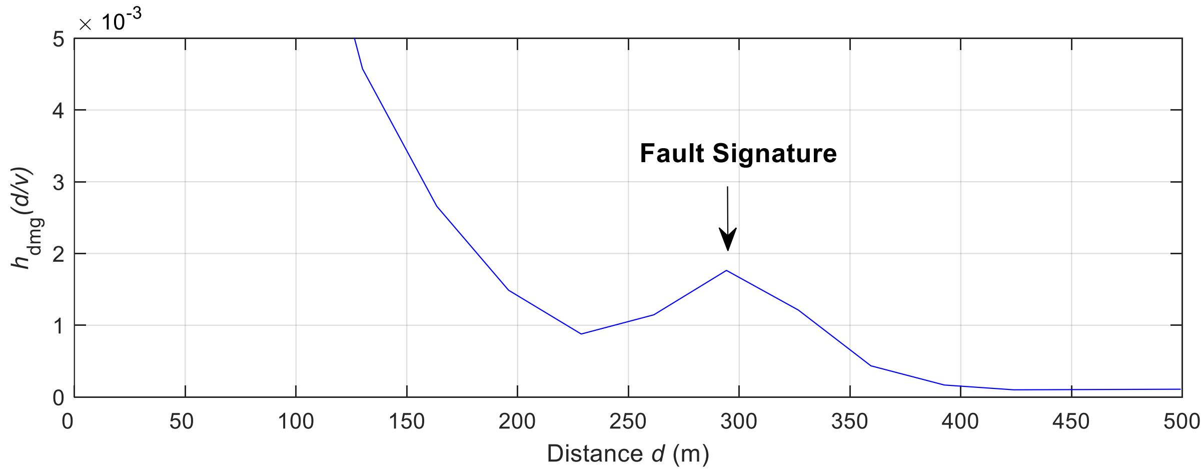
$$H_{\text{dmg}}(f) = \frac{H(f)}{H_{\text{healthy}}(f)}.$$

- By applying the *Inverse Discrete Fourier Transform*, we can obtain the *impulse response* of the damaged part of the cable, denoted by $h_{\text{dmg}}(t)$.

- This impulse response is referred to as the *damage impulse response*.

6.6. Fault Location Identification Using PLC

• The damage impulse response of the damaged cable in Example 6.6 that was estimated by the PLC modem on the receiver side is shown below.



• Here, the damage impulse response is plotted over the *distance* that the communication wave travels, denoted by *d*. Let *v* denote the *propagation speed* of communication wave. We can express *time* *t* as follows:

$$t = \frac{d}{v}.$$

6.6. Fault Location Identification Using PLC

- We can see in the figure on the previous slide that can see that the damage in the cable has created a *signature* in $h_{dmg}(d/v)$, in form of a peak at 300 m, which is twice the distance between the PLC modem at the transmitter side and the location of the damage in the cable.

- Next, we explain the reason for the above observation.

- Let L denote the length of the power line, and l denote the distance between the PLC transmitter and the location of damage on the cable.

- In Example 6.6, we have L = 1000 m and l = 150 m.

- The distance that is traveled by each communication signal in the figure on Slide 75 before it is received by the PLC modem at the receiver can be obtained based on the forward and backward path for each signal.

6.6. Fault Location Identification Using PLC

- The traveling distance of each communication signal on Slide 75 before it is received by the PLC modem at the receiver is obtained as:

$$\begin{aligned}
&① : \; L, \\
&② : \; L + 2l, \\
&③ : \; 3L - 2l, \\
&④ : \; 3L, \\
&⑤ : \; 3L + 2l,
\end{aligned}$$

- In fact, for each reflected signal, the distance traveled by the signal wave is a multiple of L plus or minus a multiple of $2l$. Thus, a peak is created in the damage impulse response hdmg(d/v) at the following distance:

$$d = 2l = 300 \; m.$$

6.6. Fault Location Identification Using PLC

- We can estimate the location of the damage by taking these steps:

  Step 1) The PLC devices continuously estimate CTF to detect major changes in H(f) compared to the historical estimation of the CTF.

  Step 2) If major changes are detected in H(f), then the relationship on Slide 79 is used to estimate $H_{\text{dmg}}(f)$.

  Step 3) Obtain the damage impulse response $h_{\text{dmg}}(t)$ by applying IDFT.

  Step 4) By using the relationship $t = d / v$, the damage impulse response is analyzed to identify the fault signature at distance d.

  Step 5) The location of the damage is estimated at distance $l = d / 2$.

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6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

• When PLC devices communicate with each other, they can measure the time that it takes for them to send and receive communication messages with each other. Such information can be used to identify the topology of the power grid that is the physical media for communication.

• The *time-of-flight* (TOF) is the time that it takes for the communication signal to travel from one PLC device to another PLC device.

• If PLC devices are equipped with GPS, then TOF can be measured by using GPS signals to precisely time stamp data transmissions, similar to how time synchronization is done in PMUs and WMUs.

6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

- If PLC devices are *not* equipped with GPS, then PLC devices can still measure TOF via a simple *two-way handshake* by using the Network Time Protocol (NTP) [142]. For example, consider PLC device A and PLC device B. The handshake consists of the following steps [418]:

  - Device A sends at time 0 a message to device B
  - Device B receives the message at time $t_1 = \tau_{AB}$, with τ_{AB} being the TOF
  - Device B sends back a message to device A after a known delay t_2
  - Device A receives the message at a known time $t_3 = 2\, t_1 + t_2$
  - Device A estimates the TOF as

$$\tau_{\mathrm{AB}} = \frac{t_3 - t_2}{2}.$$

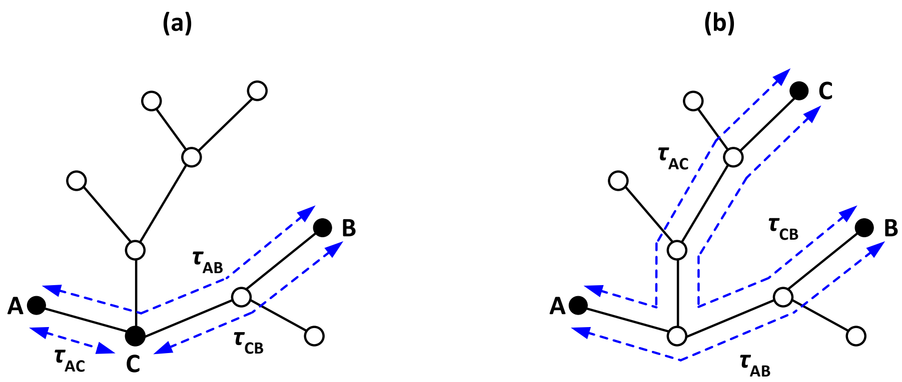
6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

- **Note**: If there are *multiple communication paths* available between two PLC devices, then TOF is the duration of the *shortest* time path between the two PLC devices. However, when it comes to a radial network topology, such as in most power distribution systems, there is only one path to communicate between any two PLC devices.

6.7.1. Topology Identification Using

• Next, consider three PLC devices A, B, and C, as shown below:



• Suppose TOF is measured among these three PLC devices and the results are denoted by τ_{AB}, τ_{AC}, and τ_{CB}.

6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

- If PLC device C *is* on the path between PLC device A and PLC device B, as in Figure (a) on the previous slide, then we would have:

$$\tau_{\mathrm{AB}} = \tau_{\mathrm{AC}} + \tau_{\mathrm{CB}}.$$

- If PLC device C is *not* on the path between PLC device A and PLC device B, as in Figure (b) on the previous slide, then we would have:

$$\tau_{\mathrm{AB}} < \tau_{\mathrm{AC}} + \tau_{\mathrm{CB}}.$$

- Similarly, we can determine whether PLC device A is on the path between PLC device B and PLC device C; and whether PLC device B is on the path between PLC device A and PLC device C.
  - This results in identifying the *relative locations* of PLC devices A, B, C.

6.7.1. Topology Identification Using

- Suppose there is a PLC device at *each bus* in a radial distribution system.

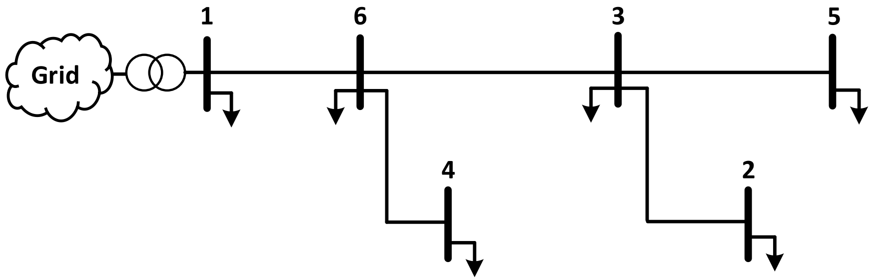
- Also suppose TOF is measured between any two PLC devices.

- By repeating the above analysis on any group of three PLC devices, we can identify the *relative location of all PLC devices* on the network.

- For a radial topology, such information on the relative location of the buses is sufficient to identify the network topology.

6.7.1. Topology Identification Using

- **Example 6.7**: Consider a power distribution system with six buses.



- Bus 1 is the substation. The network topology is radial but unknown.

- There is one PLC device at each bus. Therefore, we can refer to the PLC devices and buses interchangeably. The network is fully connected and all PLC devices can talk to each other.

6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

- **Example 6.7 (Cont.)**: The matrix of TOF measurements is obtained as

$$\tau = \begin{bmatrix} 0 & 12.64 & 10.27 & 8.04 & 13.59 & 4.47 \\ 12.64 & 0 & 2.38 & 11.74 & 5.70 & 8.17 \\ 10.27 & 2.38 & 0 & 9.37 & 3.32 & 5.80 \\ 8.04 & 11.74 & 9.37 & 0 & 12.68 & 3.57 \\ 13.59 & 5.70 & 3.32 & 12.68 & 0 & 9.12 \\ 4.47 & 8.17 & 5.80 & 3.57 & 9.12 & 0 \end{bmatrix}.$$

- The entries in are in micro-seconds. The above matrix is symmetric. The diagonal entries are zero since TOF is zero between a PLC device and itself.

6.7. Topology and Phase Identification Using PLC

6.7.1. Topology Identification Using

- **Example 6.7 (Cont.)**: From the analysis on Slide 90, we conclude that:

  - Bus 2 is not on the path between bus 1 and any other bus;
  - Bus 3 is on the path between bus 1 and buses 2 and 5;
  - Bus 4 is not on the path between bus 1 and any other bus;
  - Bus 5 is not on the path between bus 1 and any other bus;
  - Bus 6 is on the path between bus 1 and buses 2, 3, 4, and 5.

- Thus, the network topology is identified as shown on Slide 92.

6.7.2. Phase Identification Using PLC

- PLC can be used also to conduct phase identification.

- One option is to extend the topology identification method in Section 6.7.1. Suppose each PLC device is able to send and receive handshake messages on all the phases that are connected to the bus where it is installed. Accordingly, we can estimate the TOF on each phase. As a result, we can obtain matrix τ separately for each phase. We can then conduct phase identification by examining the three obtained matrices.

6.7. Topology and Phase Identification Using PLC

6.7.2. Phase Identification Using PLC

• In Example 6.7, suppose it is a three-phase network. However, suppose some buses are connected only to one or two phases. Suppose the TOF measurements are obtained separately on each phase as follows:

Phase A:

$$\tau^{\text{Phase A}} = \begin{bmatrix} 0 & 0 & 0 & 8.04 & 0 & 4.47 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 8.04 & 0 & 0 & 0 & 0 & 3.57 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 4.47 & 0 & 0 & 3.57 & 0 & 0 \end{bmatrix},$$

6.7. Topology and Phase Identification Using PLC

6.7.2. Phase Identification Using PLC

Phase B:

$$\tau^{\text{Phase B}} = \begin{bmatrix} 0 & 0 & 10.27 & 0 & 13.59 & 4.47 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 10.27 & 0 & 0 & 0 & 3.32 & 5.80 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 13.59 & 0 & 3.32 & 0 & 0 & 9.11 \\ 4.47 & 0 & 5.80 & 0 & 9.11 & 0 \end{bmatrix},$$

Phase C:

$$\tau^{\text{Phase C}} = \begin{bmatrix} 0 & 12.64 & 10.27 & 0 & 0 & 4.47 \\ 12.64 & 0 & 2.38 & 0 & 0 & 8.17 \\ 10.27 & 2.38 & 0 & 0 & 0 & 5.80 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 4.47 & 8.17 & 5.80 & 0 & 0 & 0 \end{bmatrix}.$$

6.7. Topology and Phase Identification Using PLC

6.7.2. Phase Identification Using PLC

• Note that there are several zero entries in the matrices on Slides 96 and 97. This is because several buses are not connected to all three phases, and they do not send and receive handshake messages on the phases that they are not connected to.

• By examining these matrices, we can conclude that

- Bus 2 is connected to Phase C;
- Bus 3 is connected to Phases B and C;
- Bus 4 is connected to Phase A;
- Bus 5 is connected to Phase B;
- Bus 6 is connected to all three phases.

6.7. Topology and Phase Identification Using PLC

6.7.2. Phase Identification Using PLC

- Extending the applications of TOF measurements from topology identification is not the only option to use PLC for phase identification.

- Other methods may also be used; e.g., see [423, 424].