Understanding Power Systems Protection in the Clean Energy Future

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National Renewable Energy Laboratory

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List of Acronyms

AC	alternating current
DC	direct current
IBR	inverter-based resource
PV	photovoltaics

Executive Summary

Wind power, solar photovoltaics (PV), and battery energy storage are often referred to as inverter-based resources (IBRs), which means they rely on power electronics (inverters) to generate grid-compatible electricity. This is unlike the fossil, nuclear, and hydroelectric plants that use spinning synchronous generators that have provided nearly all U.S. electricity until recently. Synchronous generators can inherently provide several services used to maintain a safe and stable grid. And as they are replaced with IBRs, it becomes important to understand how these services can be provided. One of these services is fault current, or the ability to inject large amounts of current during a short circuit. This current can easily be detected with low-cost equipment such as circuit breakers. IBRs do not inherently produce large amounts of fault current, and this may eventually require finding alternative sources of fault current or new system protection schemes.

This document, which is intended to inform policymakers and other interested stakeholders, provides a brief overview of system protection and fault current in in maintaining a safe power system. It describes why alternative approaches may be needed with increasing deployment of wind and solar generation, and it addresses various approaches to maintaining system protection in the evolving grid. An accompanying video[1] further illustrates several key concepts.

[1] "How Not to Short Circuit the Clean Energy Transition," NREL, September 29, 2021, https://www.youtube.com/watch?v=cSk5EH5bN-U&t=1s.

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Background: Power System Protection with a Changing Grid

Wind and solar provided about 11% of U.S. electricity in 2021,[2] and significant growth is expected due to declining costs and various policies encouraging deployment of renewable resources. These two power sources—along with battery energy storage—are often referred to as inverter-based resources (IBRs), which means they rely on power electronics (inverters) to generate grid-compatible electricity. This is unlike the fossil, nuclear, and hydroelectric plants that use spinning synchronous generators[3] that have provided nearly all U.S. electricity until recently. As synchronous generators, which can inherently provide several services used to maintain a safe and stable grid are replaced with IBRs, it becomes important to understand how these services can be provided with alternative resources.

One aspect of IBRs that has received great attention in recent years is the potential loss of inertial response, which helps maintain stable frequency. As a result of this increased focus, changes have been made to grid operations, and the growing consensus is that IBRs can be part of the solution to addressing frequency stability challenges (Denholm et al. 2020).

A less-discussed but also important issue, however, is maintaining proper system protection during faults, such as short circuits. Short circuits (e.g., when conductors come in contact with each other or the ground) result in very high flow of current that can damage equipment or cause fires. To prevent damage, sections of the grid experiencing fault conditions must quickly be disconnected. To recognize fault conditions, the power grid traditionally relies on synchronous generators to inject large amounts of current during faults which can easily be detected. Relatively low-cost devices like circuit breakers or fuses then disconnect the part of the grid with the fault. Using high fault currents to recognize faults in power systems is known as overcurrent protection.

IBRs being deployed today do not have the same inherent ability as synchronous generators to inject large amounts of fault current (Keller and Kroposki 2010). With increasing deployment of IBRs—and corresponding retirement of synchronous generators that is due to declining costs and increased need for decarbonization—attention is turning to how to maintain sufficient fault current capability and protection capacity.

[2] EIA (U.S. Energy Information Administration), "Total Energy: Annual Energy Review," https://www.eia.gov/totalenergy/data/annual/.
[3] They are called synchronous because they all operate at the same frequency (60 cycles per second) and in synchronism (i.e., in lock step) with each other.

Here we introduce[4] fault current and system protection with IBRs for non-specialists and an accompanying video[5] shows how fault protection can be maintained with increasing deployment of IBRs. We first introduce how fault protection is currently provided and discuss how it may be maintained with increased deployment of IBRs. Several approaches could be used to address this issue, and there is no clear consensus yet on the ultimate solution. Solutions will likely vary depending on local deployment of IBRs, existing equipment, and the evolution of both IBR technologies and complementary technologies that may be deployed in a heavily decarbonized grid.

What is Fault Protection?

For more than a century, the electric power system has relied on fault current to help protect the power grid, all the way from the power plant to your house. One of the biggest dangers of electricity use in the home is the potential for a fire caused by a short circuit.

A short circuit occurs when electricity bypasses a normal load, which typically occurs when the insulation in wires is damaged and the bare wires touch. This is illustrated conceptually in Figure 1. The left image shows the normal flow of current from an outlet through an appliance and back into the outlet. The amount of current flowing is well below the rating of the wires, illustrated by the current meter in the green. The right image shows a short circuit caused by frayed wiring. The electrical current bypasses the normal load and the reduced resistance to the flow of electricity causes a rapid rise in current through the wiring, which exceeds the safe current rating of the electrical circuit (indicated by the red in the meter).[6]

[4] For detailed explanations of power system engineering concepts, refer to textbooks and to journal articles like those listed in the references section of this document (page 11). Here, we purposely simplify concepts to make them accessible for those who do not have detailed understanding of electrical engineering concepts, such as three-phase AC, reactive power, or electromagnetic fields.

[5] "How Not to Short Circuit the Clean Energy Transition," NREL, September 29, 2021, https://www.youtube.com/watch?v=cSk5EH5bN-U&t=1s.

[6] This is due to the electrical relationship V=IR, where the voltage (V) in the circuit is roughly constant (120 V in most U.S. household circuits) and when the resistance (R) drops, the current (I) increases.

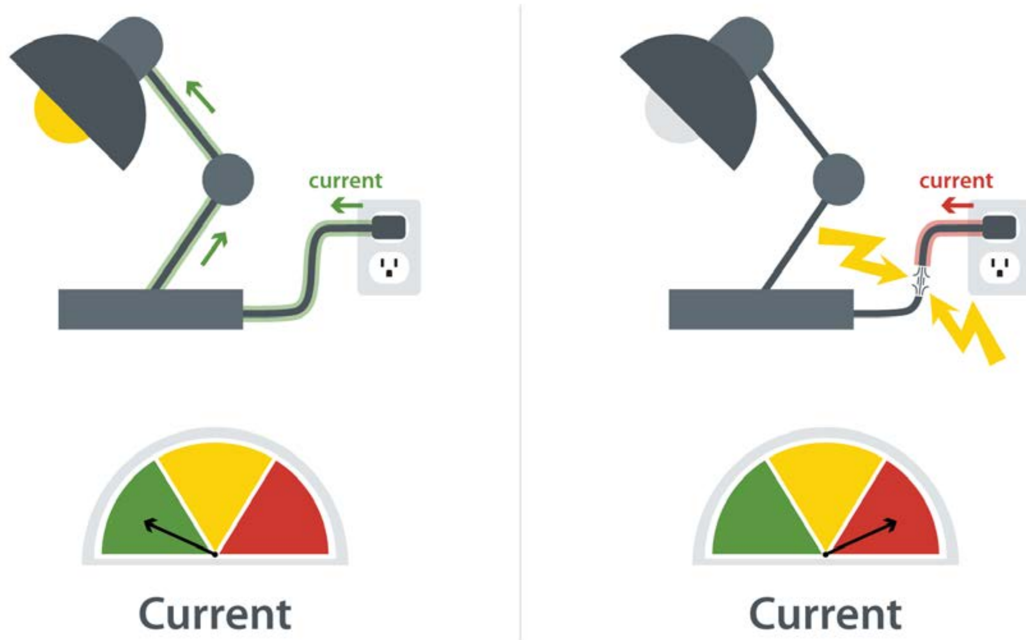

Figure 1. Short circuits and the resulting fault current

The left figure shows normal operation of a properly wired light and low flow of current.
The right figure shows a short circuit, where large amounts of current flows through the fault

The very high current flowing through the house wiring in the short circuit in the figure causes the wires to heat up.[7] The more current passing through the wiring, the hotter it gets, which is why the cord for some high-power appliances like hair driers can feel warm after using it for only a few minutes. If the high levels of current in the wires during a short circuit flow for too long without being interrupted, they have the potential to melt insulation of wiring, cause arcing, and initiate a fire.

The large current that flows through a short circuit is referred to as fault current.[8] Although this high current is undesirable due to the potential danger, the property of fault current has advantages. Because fault current produces heat, a section of wire can be inserted into the circuit to melt if the current exceeds a certain threshold. This fact underlies the basic principle of a fuse, which melts before other wires get too hot. Fuses in homes have largely been replaced by circuit breakers because of advantages including the ability to reset, provide better safety (due to no exposed electrical connections to the user), and react to more types of faults. For example, a circuit breaker can be set to react differently to a brief but very high current condition or a continuous condition of a modest overload.

These types of protective actions prevent overheating and help indicate the presence and general location of a fault so that it can be fixed. Although fuses and circuit breakers do not directly

[7] This is because $P=I^2R$. The resistance in a wire is not zero, power is dissipated—in the form of heat—in the wire.
[8] Fault current is not different from "normal" current electrically—it is just higher. It is called a fault current because it is the result of an electrical "fault" such as a short circuit.

prevent electric shocks, a tripped breaker or blown fuse signals a condition that could lead to shock and necessitates investigation.[9]

Fault Protection in the Larger Grid

The basic concepts of fault current, fuses, and circuit breakers also apply to the larger electric grid. Figure 1 shows major parts of a power grid: generators, transmission, substations, distribution, and end load (i.e., consumers). Electricity is transmitted and distributed at different voltages to maximize efficiency.[10]

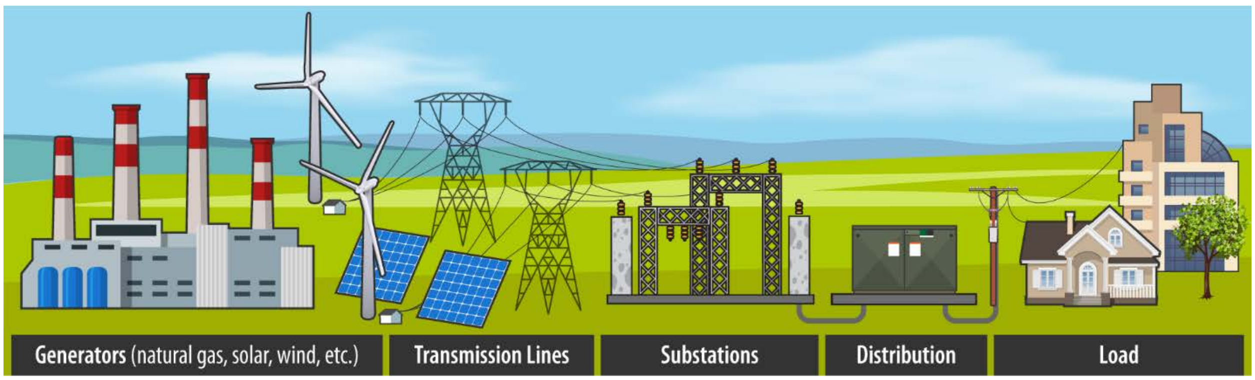

Figure 2. Components of the grid

A fault can occur in any part of the grid, so protection equipment is required that is suitable for the voltage and current levels in each section

There are many individual components between a generator and customer, including power lines and transformers, and each has a limit to how much current it can safely carry without damage. Protection equipment is placed at multiple points throughout the grid to detect current levels and "trip," or disconnect, if it exceeds the maximum current allowed in that part of the grid. These protection devices include fuses and circuit breakers, which operate in a similar manner to the ones in a house, but are much bigger and more sophisticated, allowing for varying degrees of overload for various times.

Just like in a home, fault protection on an electric grid helps prevent equipment damage and fires, but it also indicates when there is a problem that must be investigated and addressed. Fault protection isolates the section of the power grid with a fault, and it helps prevent contact with live wires under some conditions, such as a downed power line.[11] Using proper protection coordination, only the section of the grid with the fault shuts off, thus minimizing customer disruption by keeping the rest of the grid operating. In some cases, such as a fault in parts of the

[9] It is very important to recognize that although a tripped circuit breaker can indicate a potential hazard, circuit breakers are not designed to prevent injury from touching a live wire. The amount of current required to cause serious harm or death is well below what most appliances need to work, so a circuit breaker cannot act to prevent accidental electrocution.

[10] The power delivered in a line is equal to $P = IV$. So, raising the voltage (V) means the same amount of power can be delivered with lower current. And because the power (P) lost in the lines to resistive losses is equal to $P=I^2R$, lower current results in lower losses and a more efficient grid.

[11] Just as in a house, these devices on an electric grid will not prevent injury or death by interrupting the flow of electricity during accidental contact.

distribution system, doing so could result in a local blackout until the fault condition is corrected. But many faults may occur in locations where electricity may be rerouted to bypass the disconnected equipment and there will be no loss of electricity supply to customers.

The source of fault current in the U.S. grid is the collective set of synchronous generators that provide most of the electricity in today's grid.[12] Every fossil, nuclear, and hydropower plant uses a synchronous generator, as do some renewable generators that rely on steam turbines, including geothermal, biomass, and concentrating solar power generators. Synchronous generators operate at fixed voltage output and vary power by changing the amount of current produced. Under a fault condition, synchronous generators can provide about 5–6 times the normal current, which is then detected by whatever protection equipment is closest to the fault, which can be very close or very far from the generators producing the fault current.

Overall, fault current protection via devices such as fuses and circuit breakers is a cornerstone of maintaining a safe electric grid. Fault current detection relies on the basic physics of electrical current, and on relatively simple but robust devices that detect and automatically react to high current levels without any human intervention, with fault current being derived almost exclusively from synchronous generators in today's grid.

Fault Protection and Inverter-Based Resources

Inverters are required for wind, solar photovoltaics (PV), and batteries because of how these technologies produce electricity. PV and batteries produce direct current (DC) electricity, which must be converted into alternating current (AC) to be compatible with the power grid. A power electronics-based inverter converts DC electricity into AC. While wind uses a rotating (but nonsynchronous) generator, modern wind turbines also use power electronics to create a grid-compatible AC supply. Therefore wind, PV, and batteries are all considered IBRs.

IBRs have several properties that synchronous generators do not have, and this fact substantially changes how the grid must be planned and operated as IBRs continue to make up an increasing share of electricity supply. There has been growing interest, and some concern, about the loss of services provided by synchronous machines, resulting in substantial efforts to study the consequences of increasing IBRs (Kroposki et al. 2017). Table 1 summarizes several key differences between synchronous generators and IBRs. In some cases, IBRs can be programmed to provide services such as frequency response and voltage control, and they can often do so with better performance than synchronous generators due to their rapid and accurate response. Grid operators and regulators are increasingly recognizing—and exploiting—this capability, and regional and federal standards are now requiring provision these IBR services.

[12] They are called synchronous because they are all operating at the same frequency (60 cycles per second) and in synchronism (lock step) with each other. While this aspect of generators has some importance in maintaining system protection, it is their ability to automatically inject large amounts of fault current that is the focus of this discussion.

Table 1. Comparison of Synchronous Generators and Inverters

Service	Synchronous Generator	Inverter
Inertial response	Inherent physics-based response based on rotating mass and electrical characteristics of the machine	No physics-based inertia response; however, fast frequency response of the inverter can replicate inertial response in generators.
Frequency response	Provided via frequency sensing governors; can take multiple seconds for full response	Can be provided via electronic frequency sensing; can provide full response in fractions of a second
Voltage control	Provided by voltage regulator controls in the synchronous generator; typically set to keep a constant voltage as load varies.	Can be provided by sensing a voltage reference from by other generators; advanced (grid forming) inverters can independently provide voltage.
Fault current	Inherent physics-based response based on energy stored in rotating generator; generators can provide 5–6 times normal current rating for a short period of time.	No inherent response; can be programmed to provide a very rapid response but are limited by the hardware to about 1.5 times normal rating; to increase the amount of output current above these levels, inverter hardware usually needs to be modified, increasing costs.

However, the provision of fault current from IBRs cannot be addressed entirely via something as simple as changes to software. The amount of current that IBRs can provide is based on the ratings of the switches and other components used in the inverter. In a synchronous generator, the copper wire and magnets that produce the current can handle large increases in current, relative to the generator's normal rating, at least for short periods of time. In a sense, a synchronous generator produces excess current for free. But the power electronics in an inverter can only produce a small amount of additional current beyond its normal rating. Inverters self-limit the output current to protect the power electronic switching components. Therefore, under fault conditions, the amount of current typically produced by an IBR cannot significantly exceed the continuous rating of the device without causing damage.

The inability of IBR to produce large amounts of fault current can also become an issue in grids where most of the generation is from IBRs. Under these conditions there may be insufficient current to detect the presence of a fault using traditional overcurrent protection devices. The current could stay below levels that are dangerous to equipment but still produce other dangerous conditions such as increased exposure to live electrical equipment or local power quality issues. Furthermore, conditions of insufficient fault current availability are local phenomena and do not require large contributions of IBRs at the system level. Some issues, such as inertia, require significant contribution of IBRs across large areas. Insufficient fault current, however, can occur if large concentration of IBRs are deployed within a small area. This means fault current challenges could occur in some regions before others and it could occur before other issues like reduced inertia.

There are multiple initiatives to study and address the impact of IBRs on system protection, and several solutions have been demonstrated or proposed. Understanding how much "less" fault current can be produced while existing equipment can still be used without changing protection schemes is essential.

While parts of the grid rely on devices as simple as fuses, many currently deployed protection devices are far more sophisticated and they actively measure several aspects of the grid conditions that are important to system protection. For example, these devices are programmed to respond to fault conditions considering the physics-based responses from synchronous generators. It is possible that even with reduced fault current availability, many of these existing devices could, for example, be reprogrammed to recognize fault patterns that may result from increased IBR deployment.

Still, there will likely be limits to how much existing controls can be used, as under certain conditions, the fault current capacity could be insufficient to safely and reliably distinguish between extremely high but normal demand (and resulting current), and fault conditions. And if existing controls cannot be used to manage such conditions, two additional general types of options can be used to maintain fault current. In the rest of this section, we present—in a greatly simplified way—these two options, and we discuss the significant overlap between and within them.

Option 1: Maintain Fault Current-Based Protection with New Sources of Fault Current

If the supply of fault current falls below what is needed to continue using traditional protection equipment, new sources of fault current may be added as existing synchronous generators retire. Within this option, there are two potential sources of new fault current, but solutions could involve a mix of these sources.

Option 1a: Continue Using of Synchronous Machines

Synchronous generators in fossil-fueled power plants are being retired as IBRs provide a more economic source of electricity and help meet greenhouse gas emissions targets and local air quality requirements. Also, fossil-based synchronous generators can be replaced with lower or zero-emitting synchronous machines that provide fault current (and other grid services). And new nuclear or fossil plants equipped with carbon capture and storage could replace existing plants, as well as renewably fueled synchronous generators, including new geothermal, biomass, concentrating solar power, hydroelectric, and pumped hydropower storage projects. Many of these renewable technologies that use synchronous generators are typically resource- and location-dependent, and they may not be deployable where they are needed.

Though wind turbines are typically considered IBRs, it is possible to deploy wind turbines that use synchronous generators (Camm et al. 2009). These turbines, known as Type 5 machines, have yet to be deployed at large scale, in part because there has been insufficient need for the services provided by wind turbines using synchronous generators (Gevorgian et al 2022, NERC 2018). If the value of this fault current capability increases, further development—and deployment—of the technology is feasible.

An alternative source of fault current is deployment of synchronous condensers, which are electrical generators without turbines. Synchronous condensers are kept spinning using grid electricity, like a motor, but can use stored rotational energy to rapidly inject current into the grid like a generator. Synchronous condensers are well proven and widely deployed to provide a variety of grid services, including fault current. They do incur costs, though, including the inherent losses of operating a spinning machine. Synchronous condensers can be repurposed from retiring generators using existing infrastructure. They can also be added to new or existing power plants via a clutch that allows the plants to operate as synchronous condensers even if they are not needed for energy. Another possibility could be using new or retrofit gas turbines that burn renewably derived fuels. For example. hydrogen or other renewably derived fuels could be used in modified combustion turbines that have the same characteristics of natural-gas fired turbines. Furthermore, they could also use clutched synchronous condensers providing fault current even when not generating electricity. This capability could also be added to Type 5 wind turbines, which means wind could provide grid services including fault current and mechanical inertia even when the wind turbine is not producing electricity. And this collective set of options could potentially meet the fault current needs of the existing grid with minimal changes to existing system protection schemes.

Option 1b: Add Fault Current Capacity to IBRs

The main reason IBRs cannot provide fault current today is lack of incentives. Adding fault current capability incurs a cost because of higher-rated inverter components. Without a need for this capability, IBR manufacturers and developers have no incentive to add it. The costs of adding higher current capacity from IBRs can be estimated, but doing so requires understanding the actual amount of additional current capacity needed, as well as when it is needed, especially given the variable nature of PV and wind. Furthermore, although it is possible to "oversize" inverter components, there are potential interactions between software-based fault current injection from IBRs and the remaining synchronous generators that inherently provide it. Overall, it is well understood that IBRs can provide fault current, but the actual need, design standards, and business case have yet to be established (Keller et al. 2012). It is important to explore this possibility, because IBRs could be a lower-cost source of fault current than synchronous machines.

Option 2: Implement Alternative Protection Schemes

Like many aspects of grid operation, existing protection schemes are based on the characteristics of legacy equipment, including synchronous generators. However, in the design of a grid around modern technology including IBRs, alternative approaches could ultimately result in lower costs. Option 1 focuses on what are called overcurrent protection schemes to recognize large amounts of fault current seen during faults. Efforts are ongoing to design alternative protection schemes that do not rely on large fault current to trigger protection equipment (Brahma 2019; Haddadi et al. 2021; Blaabjerg et al. 2017). These approaches leverage modern computation, communications, and measurement capabilities, and while complicated, they could provide lower-cost alternatives to the more hardware-based solutions described in Option 1. Such approaches would require a transition from the existing protection schemes over time as more IBRs are deployed on the grid.

One example of such an approach is to add sensors to measure the flow of current at many points on the grid and then compare the resulting measurements to what they would be under a range of normal conditions (Velaga et al. 2021). Deviations could indicate a fault, and signals could then be sent to disconnect the part of the grid with the fault. Such schemes have been demonstrated in microgrids, including some with significant IBR contributions, but they have not been deployed in larger grids, as IBR deployment levels in large grids have not necessitated alternative approaches (Manson and McCullough 2021; Ropp and Reno 2021). And there is considerable uncertainty about the optimal and most cost-effective approach for these protection schemes.

Summary

There has been considerable effort to evaluate the changes in grid planning and operation associated with large-scale IBR deployment. It appears likely that loss of fault current from retiring fossil-fueled synchronous generators will need to be addressed to maintain adequate system protection. There are a range of options to maintain system protection, including some that are very well understood and have a high degree of certainty, such as synchronous condensers. Others, such as entirely new protection schemes that do not rely on large fault current, are in earlier stages of development, and while uncertain, could ultimately provide the same or even improved levels of protection at a lower cost. So, while there is little doubt that maintaining adequate system protection with increased deployment of IBRs will be possible, there is significant uncertainty about the best approach. Perhaps the biggest challenge to determining the cost-optimal mix of resources is understanding both the need and cost of various options, which will likely vary significantly based on location and mix of existing and future resources.

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