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At the March 5, 2010 UW-Madison Chemistry Department Colloquium, Prof. Bassam Z. Shakhashiri, the director of the Wisconsin Initiative for Science Literacy (WISL), encouraged all UW-Madison chemistry Ph.D. candidates to include a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

Over 50 Ph.D. degree recipients have successfully completed their theses and included such a chapter.

WISL encourages the inclusion of such chapters in all Ph.D. theses everywhere through the cooperation of Ph.D. candidates and their mentors. WISL is now offering additional awards of $250 for UW-Madison chemistry Ph.D. candidates.

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Impact of Inverter Control on the Dynamic Performance of Power systems with High Penetration of Inverter Based Resources

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy
(Electrical Engineering)

at the
UNIVERSITY of WISCONSIN - MADISON
2020

Date of final oral examination: 4/28/2020

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Preface

This chapter was written in collaboration with the Wisconsin Initiative for Science Literacy (WISL) to communicate my Ph.D. research to non-specialists. I would like to thank WISL for giving me this opportunity and for providing guidance and editorial support. I commend this initiative for providing a forum to motivate Ph.D. students to broaden their horizons and reach a wider audience. During my stay at UW, I have had a chance to talk to many non-specialists including middle school children/teachers, journalists, scientists in other backgrounds, etc., through public forums. Personally, I have gained a unique perspective through my conversations by viewing my problem through different eyes. It is thus an honor to present my research in this chapter to appeal to the broader audience. I have taken the best of my effort to communicate the content without much background knowledge about electrical engineering or electricity power grids.

Chapter 1 : Thesis Excerpt for Non-Specialists

1.1 Background

1.1.1 Electric Power Grids

Electricity has become an essential and ubiquitous commodity to the point that the system that generates, transmits and distributes electricity hardly ever gets noticed. However, it is worthwhile to understand that the electric power grids are the biggest operating machines in the world. They span large geographic areas and include thousands of power plants (such as coal, nuclear, hydroelectric etc.), over a hundred-thousand miles of transmission lines, tens of thousands of substations, transformers and other transmission and distribution system infrastructure. The power system operators manage this huge infrastructure and make it work coherently in order to generate, transmit and distribute electricity to every single residential and industrial consumer.

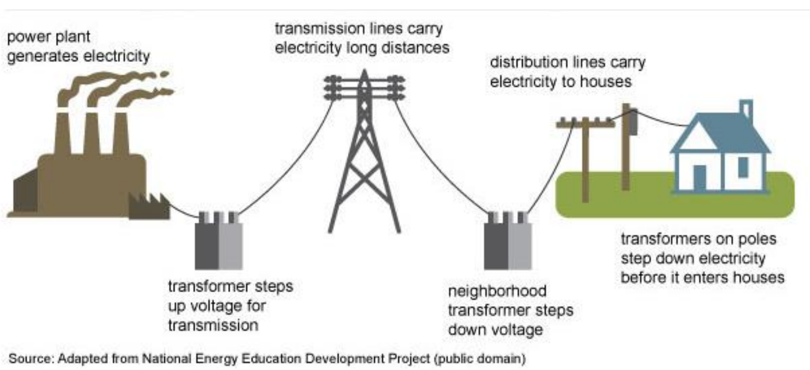


Fig. 1.1. Electricity generation, transmission, and distribution [1]

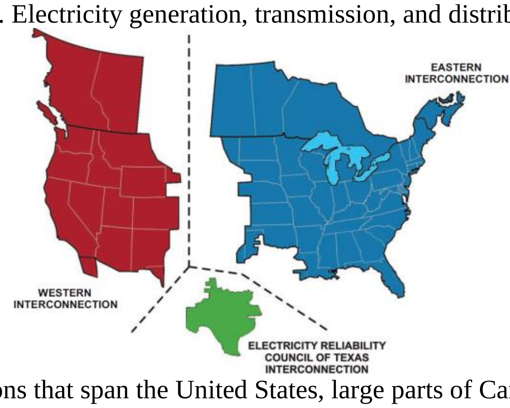


Fig. 1.2. Electric interconnections that span the United States, large parts of Canada, and a small part of Mexico
Credit – US Department of Energy

In the U.S., (48 contiguous states along with Canada and some parts of Mexico), there are three major electricity grids – the Western interconnection, the Eastern interconnection, and the Texas

Interconnection. It is hard to believe that there is a physical connection between every single customer and all generating plants in each electric interconnection. In effect, the generated electricity is transported to each customer using a complicated network of transmission lines, transformers, substations, etc. The network structure of the interconnections helps maintain the reliability of the grid by providing multiple routes for power to flow and allowing generators to supply electricity to many load centers [2]. Operating this huge and sophisticated infrastructure to ensure reliable supply of electricity is a formidable feat of engineering.

Unlike other networks such as communication networks (telephone, internet), the electricity grid requires a highly coordinated operation of the entire infrastructure. It is important to note that electricity is not stored on a large scale; every small change in consumer demand such as turning on a fan or a bulb needs to be produced almost instantly by the generators by burning more coal or pumping more fuel to the power plant. The electricity supply must constantly meet the electricity demand to ensure stable operation of the power grid.

It is not uncommon for things to go wrong in such a huge system. Protection infrastructure is present at various stages in the power grid to isolate a disturbance event. Such events can be as benign as a blowing up of a microwave oven in a home or a tree falling on a distribution line, or something major such as collapse of a transmission line or the abrupt shutdown of a power plant. The system is generally designed to handle such events, to an extent, and can sustain such disturbances for a brief period of time. However, a single serious event can lead to a cascaded failure of the entire system and can result in a blackout. The system operators monitor the system continuously using a variety of sensors in real-time and ensure the correction operation of a variety of protection mechanisms. Power system engineers constantly study different scenarios and propose solutions to ensure reliable operation of the electric grid.

The War of Currents – AC vs DC

While speaking of electricity grids, it is important to note that there are two major forms of electricity – AC (alternating current) and DC (direct current) [3]. Direct current (DC) flows in a single direction, like in a battery, whereas AC switches the current directions a certain number of times every second (Fig. 1.3). Throughout the world, AC electricity is used in the power grids, as it has proved to be the most efficient way to transmit electricity over large distances. The electric generators produce electricity as AC, which is then transmitted and distributed. In the U.S., the standard voltage at the residential level is 120V, with a frequency of 60Hz (the voltage alternates 60 times in one second).

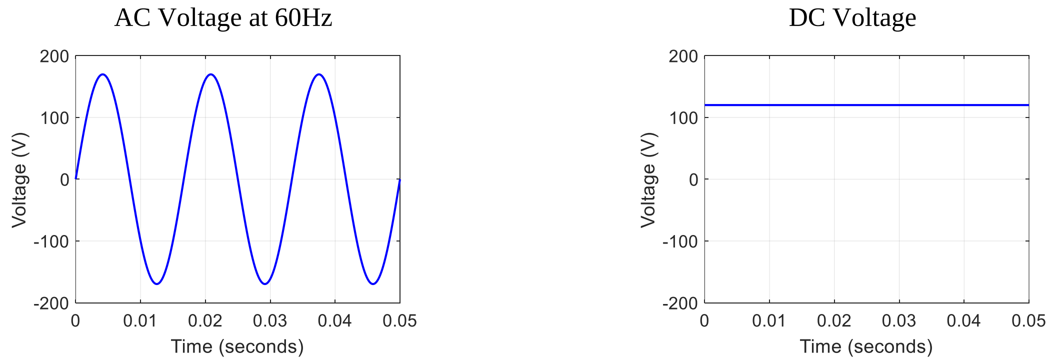
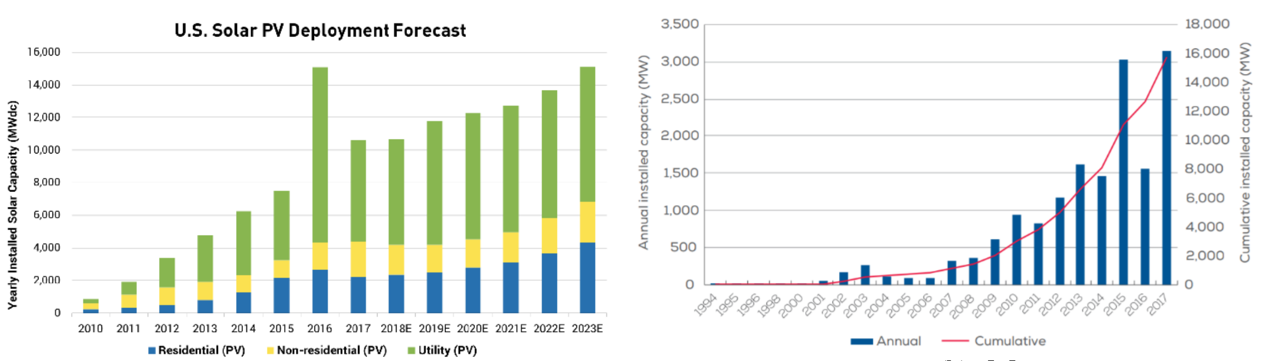


Fig. 1.3. AC vs DC voltage waveforms

1.1.2 The Paradigm Shift

In recent years, the electric power grids in many parts of the world have been undergoing a paradigm shift due to displacement of conventional sources such as coal and nuclear power plants with renewable sources of energy. The installations of variable renewable energy (VRE) resources such as solar panels and wind turbine generators has grown rapidly during recent years. Solar panels convert incident light to electricity and are referred to as photovoltaics (PV). Fig. 1.4 (a) shows the annual deployment of PV in the United States, where a consistently increasing trend in annual installed capacity is observed.



(a) [4]
(b) [5]

Fig. 1.4. (a) Annual PV power installations in the United States (past and projected) (b) Annual and cumulative installed off-shore wind capacity in Europe

A similar trend can be observed for off-shore wind installations in Europe [(b)]. Many countries around the world including the United States, Australia, Denmark, Finland, Germany, Australia, etc., have a large capacity of VRE sources in their power system. The cost of installing utility-scale PV power plants has reduced drastically over the years and has resulted in the widespread adoption of PV by many power system operators. In fact, it is more economical to install a solar farm than install a coal power plant. The commitment to renewable energy is growing due to both economic and environmental reasons.

Many regions/countries have proposed ambitious renewable energy targets. The state of Hawaii in the U.S has committed to 100% renewable energy by 2045 [6]. The state of California has mandated that every newly-constructed home must have a rooftop PV installation starting in 2020, and the state has committed itself to achieving 100% carbon-free electricity by 2045[7]. Germany has a 45% renewable energy target by 2030[8]. In addition, renewable portfolio standards (RPSs) adopted in such regions have mandated utility operators to produce a specified fraction of their power from renewable sources.

1.1.3 Challenges in the Electric Grid due to Renewable Generation

The widespread adoption of renewable energy sources is forcing changes in the operating characteristics of the electric power system. The obvious problem is the mismatch between supply and demand. Conventional resources are generally dispatchable; by controlling the fuel input, such sources can vary their power output. However, solar panels and wind generators are both variable sources and are volatile by nature. The power output of these resources is dependent on natural phenomenon, i.e. wind and irradiation, which are especially hard to forecast. Due to the lack of large-scale energy storage in the electricity grids, the intermittency of these sources results in scheduling issues and there is often a mismatch between generation and consumption (supply and demand) with high levels of renewable generation. The peak generation of solar even on a sunny day does not typically match with the hours of peak load demand.

The variability of these sources causes problems at multiple levels. The rapidly changing output from such sources needs to be compensated by other sources. This requires keeping other conventional power plants (such as coal) operational, thus reducing the economic advantage. In places with a high number of residences with PV on the rooftop, variations in voltage levels outside the conventional margins have been observed. In this thesis, a far more important problem is considered- Can the system even operate reliably at high levels of renewable generation? Can the power system network maintain its "***stability***" with increasing renewable penetration levels? [9]

What is stability, why does it matter?

In a general sense, dynamic stability is the ability of any system to gradually return to its original state when disturbed from it. For example, for a rocket or an aircraft to be stable, it should be able to stay afloat in air and maintain its desired trajectories despite external conditions. A similar concern applies to the largest operating machines in this world! Operating a stable power system is vital to continually deliver power to consumers. However, changes in the system characteristics in recent times due to integration of renewable sources has increased concerns among power system operators. It is shown in thesis that there are serious threats to system stability due to the difference in operating mechanism of these renewable sources.

1.2 Operating Mechanisms of Conventional and Renewable Generation

1.2.1 Conventional Power Plants

Physics of Power Plants - Conventional generators such as coal, nuclear, hydroelectric etc., power plants convert mechanical energy to electrical energy. By burning coal or nuclear fuel, the heat generated is used to vaporize water to steam, which is used to rotate huge turbine blades. In hydel power plants, this rotational force is produced from stored potential energy (such as waterfalls or dams). The rotating turbine is coupled to an electrical generator that converts mechanical energy to AC electricity. This electric generator is essentially a huge alternator. Small alternators are commonly used in automobiles; they use the car engine's rotation to charge the battery and to power the electrical system. The electric generator operates in a similar manner, with the rotational force caused by pressurized steam or water flowing at a high speed.

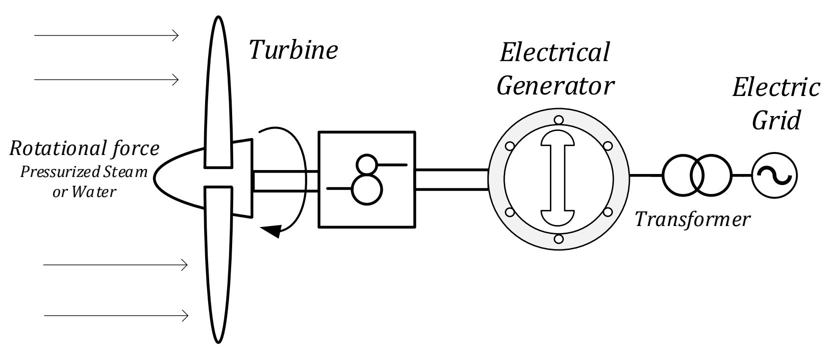


Fig. 1.5. Basic diagram of a conventional power plant

Electromechanical Energy Conversion

The mechanism of energy conversion can be easily understood by comparing it to driving a car or any automobile. If a car is driven uphill, it would start slowing down unless the driver presses the accelerator pedal. This is because the engine has to produce more force to overcome gravity. Pressing the accelerator pedal releases more fuel to the engine. While going downhill, the speed increases unless the brakes are pressed to dissipate excess kinetic energy. Even if the car is set to cruise mode (maintaining a fixed speed), one might notice that the speed dips temporarily while going uphill and increases temporarily while going downhill.

The electric generator is in fact operated in an analogous manner (in cruise mode) to regulate its rotational speed. If the electrical load increases (such as turning on a fan or a bulb), the generator would start slowing down unless more fuel is injected. However, the mechanical response is much slower compared to a car. This is due to the large size of the generators, which causes a huge inertia. The response time for adjusting speed is relatively slow and usually takes a few seconds to act. The typical response of this speed after such a transient event is shown in Fig. 1.6. The speed dips initially and later bought back to nominal over time.

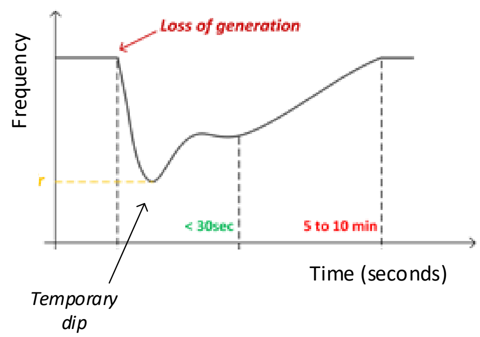


Fig. 1.6. Typical grid frequency response to a loss of generation event

Stored Kinetic Energy

Earlier in this chapter it was mentioned that there is no large-scale energy storage in the electrical power system. However, there is a small amount of energy stored as kinetic energy in the rotating shaft. In the car analogy, the reason the speed of the car dips temporarily while going uphill is because enough fuel isn't supplied to the engine. There is a delay before the engine begins to act. In this interval, the stored kinetic energy in the rotating engine is partly used to actually keep the car moving. Hence, the stored energy is meaningful. In the generator case, the stored kinetic energy is responsible for supplying power when there is immediate need, before more fuel can be released. In fact, the inertia of the large generators is considered somewhat responsible for maintaining system stability. Without this stored energy in the form of shaft inertia, there would be no means to support the system during transient events.

What is "Frequency"?

The main feature of the electromechanical energy conversion is the link between electrical and mechanical processes. The electrical frequency(~60Hz) is in fact this link. The frequency of the voltages produced by the generator (i.e. ~60Hz) is directly related to the rotational speed of the generator. Hence, the response of the electrical frequency directly indicates the response of the rotor speed.

Synchronization Among Multiple Generators

To understand synchronization, one can visualize an imaginary system of multiple cars towing a big crate. Assume that each car is connected to the crate through a spring. To make sure the cars do not collide with the crate, each car should maintain the exact same speed and relative position. This will spread the towing power among all cars. This is an example of synchronization! The spring in this example restricts relative motion between the cars and the crate. Yet, it allows temporary differences between speeds of the cars and the crate. Temporary differences are natural because not all cars are the same! If the cars are moving uphill together, a more powerful car can accelerate easier than a less powerful one. To prevent a crash, each car should ultimately come back to the same speed and maintain the same relative position with respect to other cars.

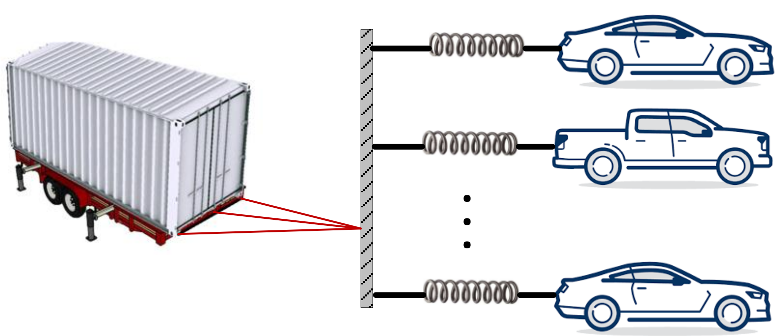


Fig. 1.7. Multiple cars pulling a big truck

There is a directly analogy between this car network and network of electrical generators. For an AC electric network to operate and deliver power continuously, the laws of physics dictate that all sources should operate at the same frequency (i.e. the voltages should have the same frequency). In essence, all the generators should rotate at the exact same speed to continuously deliver power. These generators are said to be "synchronized" with each other. A disturbance event can cause this frequency to change temporarily as in Fig. 1.6., but it should eventually settle to be uniform throughout the system in a stable network.

In the AC network, each generator spins somewhat independently and does not depend on other generators for setting its speed. This ensures that there is no single “master” generator responsible for setting the system frequency. All the generators act as “masters” by independently controlling frequency and yet maintaining synchronism. In the analogous car system, there is no single “master” car that decides what the speed should be that others should try and follow. If the only master car malfunctions and disconnects, the entire system would fail. Instead, if all the cars were masters, even if one of the cars fails, the car network would still be operational. Likewise, the failure of the “master” generator would instantly lead to system collapse. Since this is not the case, tripping of any single generator would not lead to collapse of the system. The other generators would still control the frequency and helps in achieving reliable system operation. Hence, generators are referred to as “***Grid-Forming”*** sources, i.e. sources that can control their own frequency and form the basis of the electric grid.

1.2.2 Renewable Generation (Inverter Based Resources)

Physics of Solar and Wind Generators

Solar arrays have a different science behind them and operate in a fundamentally different sense. Light radiation falling on photosensitive cells is used to directly move these electrons. Solar photovoltaic (PV) arrays produce DC electricity, which must be converted to AC to be interconnected with the electric network. Semiconductor devices called power converters are used for this conversion process. Since the power is converted from DC to AC, these power converters are often specifically referred to as “***Inverters***”. The same devices are used even with wind turbines. While the working of a wind turbine might look similar to a conventional power plant (rotational energy to electricity), the wind speed is generally too low to directly produce an AC voltage which alternates at 60 cycles per sec (60Hz). While old wind generators have used mechanical gears for stepping up the speed, modern wind generators do not follow this inefficient approach. Most modern wind generators work similar to a PV array from an electrical standpoint, i.e., they produce DC electricity which is then converted to AC using an intermediate power converter. Hence, these resources are generally referred to as Inverter-based Resources (IBR).

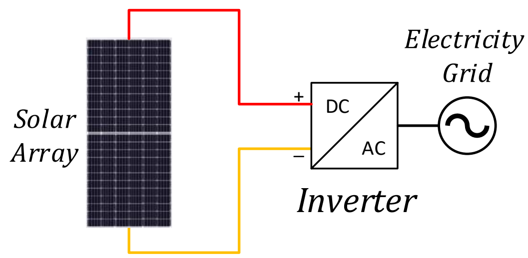


Fig. 1.8. Solar array connected to the electric grid

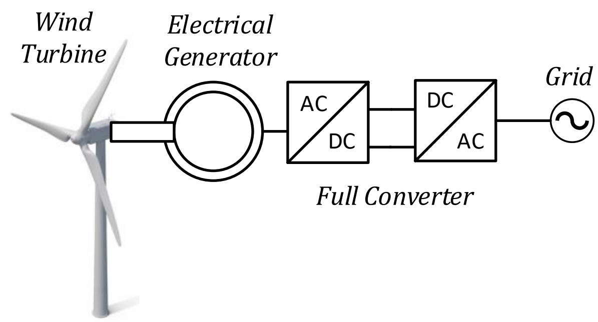


Fig. 1.9. Wind turbine connected to the electric grid

How do Inverters work?

While the energy conversion process looks simple enough, the operation of these inverters is quite complex. The semiconductor devices used in these inverters are controlled based on signals from an onboard digital processor. In essence, the behavior of these inverters can be programmed on this processor. The inverter is programmed to continually monitor electrical quantities such as voltages and currents using sensors as feedback to operate a real time control system. This helps operate reliably under varying conditions such as irradiation levels and remain synchronized with the electric grid. Typically, these inverters are programmed to continually extract the maximum power that can be obtained from the PV array or wind turbine.

How do Inverters Synchronize with the AC network?

Inverters cannot naturally synchronize like conventional generators do because they do not have a rotating component that dictates frequency. In order to synchronize, the inverters continually measure the grid frequency at the point at which they are connected to the network. By definition of this synchronization mechanism, they act as "slaves" in this system since they do not actively participate in producing an independent frequency. Without the presence of a "master" source, these sources cannot continually deliver power in in an AC network. Such sources are referred to as ***"Grid Following"*** sources as they are said to follow the grid voltage at its terminals.

In the imaginary car system, one can imagine having a racing car connected to the crate (as an equivalent way of connecting inverters). The racing car is completely different from a car and does not behave the same way a regular car operates. The equivalent of operating a grid following inverter is to make the racing car follow the crate. Here, the speed of the crate would be maintained by the other cars. The racing car does not contribute to the speed of the crate, it merely follows the other cars. This works fine as long as there are enough cars to actually control the speed. Doing so prevents the confusion of operating a new technology without disturbing the existing one.

This operating principle (***grid-following***) has been commonly adopted for these sources since their inception and is used in all commercial inverters. Historically, the electric grid was dominated by conventional generators and the contribution from renewable sources was insignificant. The mechanism of electricity generation of renewable sources has been assumed to not impact the system performance. However, the widespread adoption of renewable sources has triggered concerns regarding their operating mechanisms.

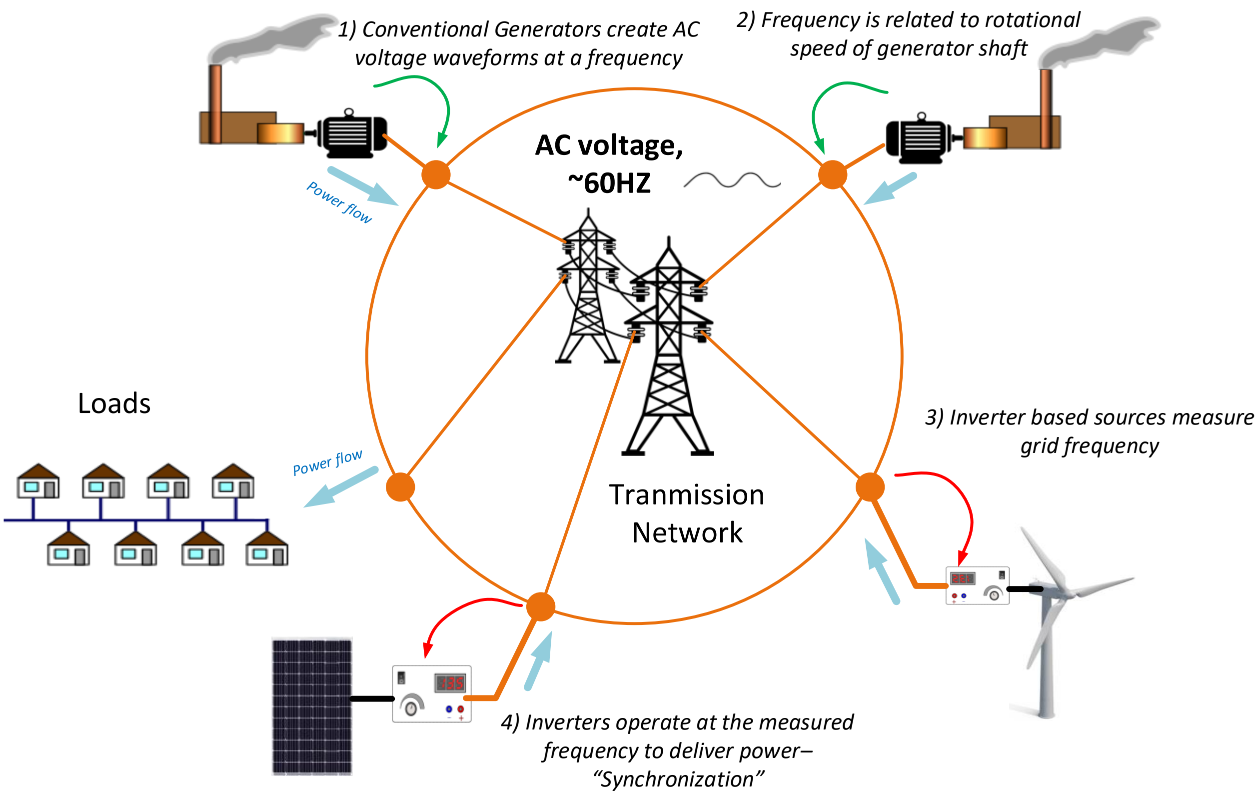


Fig. 1.10. Synchronization of Inverter based resources

1.3 <u>Challenges in Power System Stability</u>

As mentioned earlier, renewable sources are not dispatchable; they always inject whatever power is available to them. The variability in grid (such as turning on fans and microwave ovens) are typically supplied by the conventional generators. Further, a cloud cover that might reduce the output of a solar array, will have to be compensated by conventional generators. At the same time, some conventional generators are being phased out and they are often displaced by newly installed renewable sources. It is not economical to keep operating all conventional generators along with the renewable sources. This leads to some major concerns with maintaining power system stability.

In the car example, this would be equivalent to having the racing cars that follow the crate provide a constant pulling power despite what terrain the cars are going in. If going uphill, this constant pulling power might not be enough. When going downhill, this constant pulling power might be too much. Hence, the cars bear the burden of adjusting to all variations.

1.3.1 Lower Stored Kinetic Energy (Low Inertia)

As described earlier, it is the stored kinetic energy in the shaft of conventional generators that is used as a buffer during transient events. However, most inverters do not contribute to stored kinetic energy (they do not have moving parts). Lower stored kinetic energy (or low inertia) is among the top concerns for many power system operators[10]. An immediate effect of this low inertia is large frequency deviations during transient events. In the imaginary car system, the speed of the system would deviate much more when going uphill or downhill because the racing cars provide only a constant pulling power and do not adapt to their terrain.

A simulation of the Texas electric grid shows the response of the grid frequency for a disturbance event at different penetration levels [11]. The same event cases significantly large deviations at higher levels of renewables.

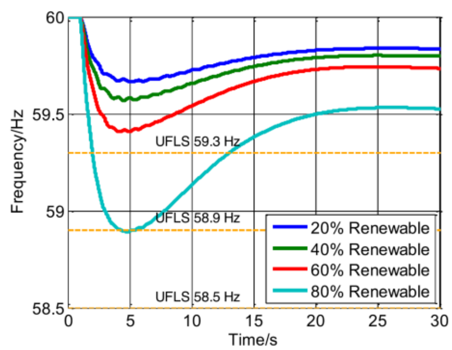
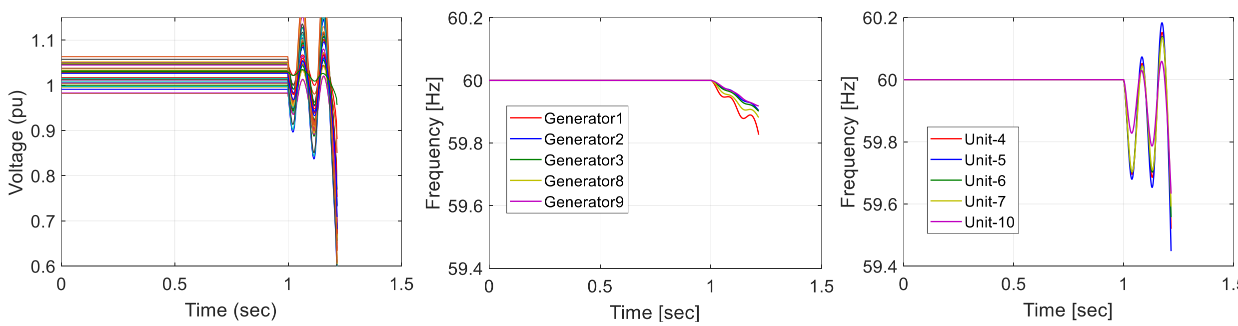


Fig. 1.11. Simulated grid frequency response at increasing levels of renewables [11]

1.3.2 Lack of Grid Forming Sources for Inverter Synchronization

In the car system analogy, the racing cars just follow the speed of the crate. If all are racing cars, then there would be no car to decide the speed of the system! Hence, some normal cars are always required to decide the speed. The next question is - how many? A similar idea applies to the power system. Conventional generators are always required to make sure the system operates at a specific frequency. Due to displacement of conventional sources with inverters, the number of sources that can maintain system frequency keep declining. However, the question is how many normal generators are required?

In this thesis, this synchronization method was analyzed in detail with varying levels of renewable penetration. The study revealed that this synchronization mechanism fails at with higher levels of renewables, but the exact level is dependent on the electrical system. It was predicted that this synchronization mechanism failure could be accelerated in cases where these renewable sources are far away (likes hundreds of miles) from the conventional generators. An example simulated plot is shown in Fig. 1.12: nearly 50% of the power sources are renewables. A small disturbance is applied in the power system at the time instant of 1sec, which results in the collapse of the system. The major observation is that the frequencies measured by the inverter are significantly different from the generator frequencies. The measured frequencies have significant oscillations and results in an unstable response that collapses the entire system.



(a) Bus Voltage Response (b) Generator Frequencies (c) Measured Inverter Frequencies

Fig. 1.12. Simulated waveforms for ~50% renewable penetration

1.3.3 Lack of Grid Support Capability

Along with the synchronization problem and inertia-related challenges, inverter-based resources also lead to other integration challenges. Inverters were originally designed not to change system behavior significantly. In some cases, inverters disconnect at the first sign of any trouble sensed in the system! With growing penetration of renewables, this approach does not work anymore. Disconnecting these sources could lead to huge mismatch between supply and demand. Inverters would have to support the system by riding through such disturbances and helping maintain the system stability. Without changing their original behavior, inverters would require additional devices to provide this support. Such devices would increase the cost of electricity, which ultimately falls on the consumer. Standards are being studied and proposed for improving grid support capability of these inverters. However, these apply only to newly installed sources. The system operators still face many challenges with older generation inverters.

1.4 Proposed Solution- Grid Forming Inverters

In the imaginary car system, the solution might seem obvious; make the racing car behave like cars! Even though the racing car is quite different, it could essentially operate like a normal car. While going uphill, the racing car could accelerate and share the pulling power based on the terrain. A similar analogy is applicable with inverters. Inverter based resources include embedded processors that can be programmed to define their behavior. The proposed approach involves making inverters behave like conventional generators with respect to their operating mechanism. In this thesis, this approach is investigated in detail.

Conventional power plants operate as grid forming sources because they can control frequency independently. Inverters can be programmed to do the same thing and behave as grid forming sources. Even though they do not have a physical phenomenon to link to frequency, they can emulate this behavior virtually. By emulating a behavior similar to conventional power plants, they can avoid significant problems in power system stability. In fact, they can do better than them! By programming these inverters in a certain fashion, the power system stability can be proved to be better than with conventional generators! The study of this approach and proving the improvement in system performance is the primary objective of this thesis.

1.4.1 Inverters operating as Grid Forming sources – History

Previous research at UW Madison (that goes back nearly ~25yrs!) has studied operating inverters as grid forming sources. The initial application was limited battery backup systems for commercial buildings where power supply is extremely critical (like computer servers, or communication towers etc.,) [12].

1.4.2 How is the frequency determined in Grid Forming Inverters?

Controlling the frequency is the key to the operation as a grid forming source. But how do you do so? In the car example, the speed decrease from driving uphill is overcome by pumping more fuel to the engine. Using the same analogy, the power output of the renewable source can be linked to the frequency. If the frequency decreases (car going uphill), then the power output should be increased (pumping more fuel). The frequency is varied in a direction opposite to the change in power. For example, if the power output of the inverter increases, the frequency decreases and vice versa.

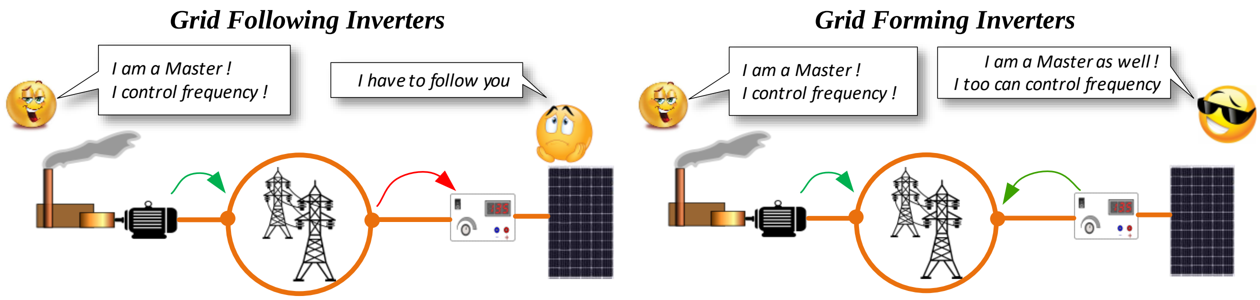
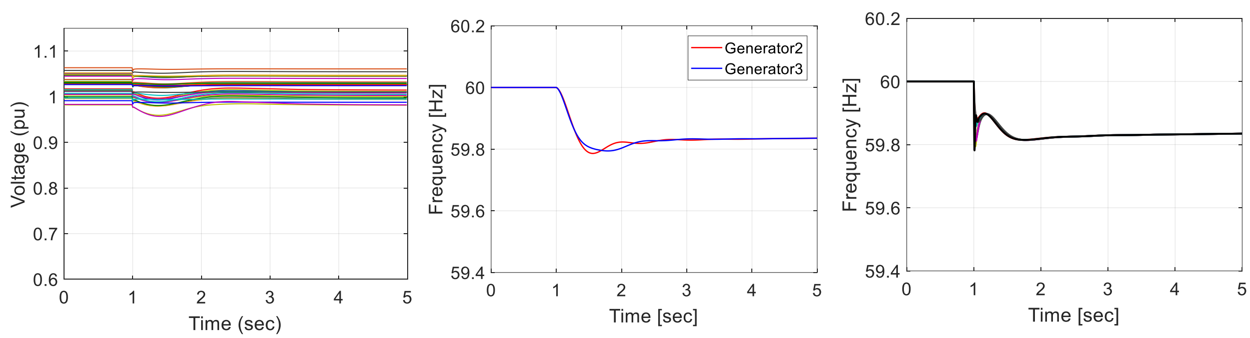


Fig. 1.13. Synchronization of Inverter based resources

1.4.3 How do they synchronize with the rest of the network?

By linking frequency to a physical phenomenon (electric power), the inverter can naturally synchronize with the system. The synchronization process is very similar to a conventional generator. In this work, extensive studies have shown that these inverters can work hand in hand with traditional generators. An example plot is shown in Fig. 1.14., where the inverter frequencies can track the generator frequencies after turning on a big load(like a factory). There is a small difference in the transient behavior between the inverter frequencies and generator frequencies due to the fundamental difference in operating mechanisms. Generators change their speeds slowly, whereas the inverters respond instantly. Nevertheless, the inverters track the generators speeds subsequently. This is significantly different from the unstable response in Fig. 1.12. due to grid following inverters that couldn't synchronize with the AC network.



(a) Bus Voltage Response (b) Generator Frequencies (c) Inverter Frequencies

Fig. 1.14. Simulated waveforms for ~80% renewables operating as Grid Forming Inverters

1.4.4 Don't these Inverters require stored energy (inertia) like conventional generators?

In this thesis, the concepts of inertia and stored energy are demystified. Conventional generators need stored energy because they respond slowly to load changes. The change in fuel input by governor action takes a few seconds in these generators. However, inverters do not have any such slow responding mechanical parts! Like the racing car can accelerate much faster than other cars when going uphill, the inverters can adjust their power outputs almost instantly. This benefits the entire system in a positive way. In fact, it would be much easier to pull the entire crate uphill because of the benefits of having a racing car. The racing car naturally has low inertia because it can accelerate and brake extremely quickly.

In this thesis, it was proved that lower levels of inertia are not an issue anymore if there are sufficient grid forming inverters in the system. Due to their instant response, these inverters can directly arrest large frequency deviations. An example plot is shown in Fig. 1.15. where nearly 70% of the sources are renewables. A big load is turned off (like a huge factory) at 1sec and the response of generator speed(frequency) is shown. The frequency increases significantly with traditional grid following inverters, whereas it arrested almost instantly due to the presence of grid forming inverters.

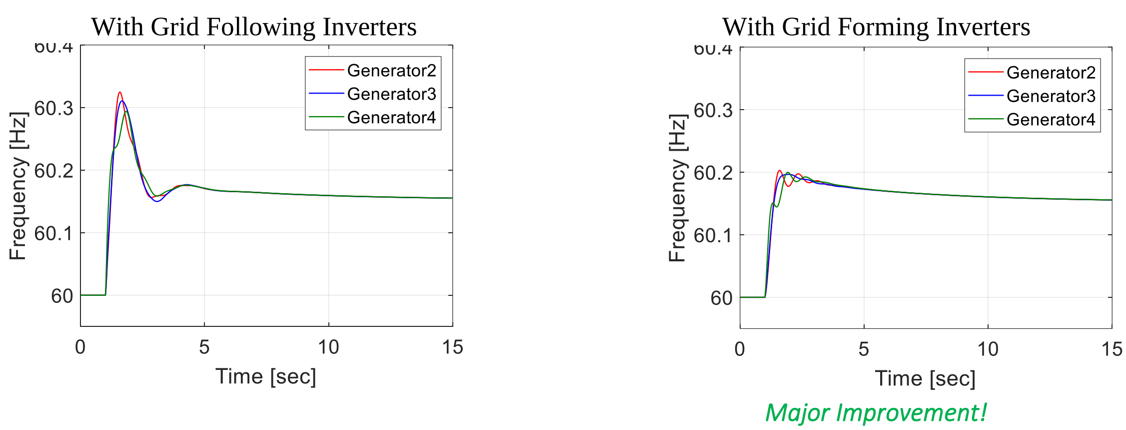


Fig. 1.15. Generator Frequency response at ~70% inverter penetration

1.4.5 Can they support the system by offloading conventional generators?

As mentioned earlier, traditional inverters always operate to deliver the maximum available power output. They do not respond to changes in the system load. All load changes are handled by conventional power plants. This was motivated by economic reasons, to maximize the power capability of renewable resources. However, this approach is not deemed to be beneficial anymore. The cost of renewable sources has come down significantly and renewable sources have become a significant contributor to the total delivered power. It is necessary for such sources to participate in load changes and avoid overloading conventional generators and keep conventional generators operational. Hence, such inverters have to be programmed to operate lower than the maximum capability of the resource and have some reserve capability (say ~20%) to meet load changes. The cost of reducing their output power is significantly more than the cost of operating an entire conventional coal power plant which could otherwise be retired.

1.5 What is next for Grid Forming Inverters?

Based on the results from this research, there is compelling evidence to suggest that operating renewable, inverter-based generation as grid forming resources can lead to improved system performance. Grid forming control approaches are currently being studied by many power system operators and inverter manufacturers. However, grid forming inverters still face some challenges for integration in commercial applications. They are still not well established and are still being researched to be reliable under a wide range of grid operating conditions.

There are two major hurdles in the path of adopting this technology – 1) value proposition, i.e., promise of an added commercial value, and 2) policy/standards. These inverters should offer sufficient value proposition for a commercial manufacturer to adopt this technology. While scientists know that maintaining power system stability is of foremost value, utility operators are generally skeptical of new technologies and are unwilling to adopt them without well proven benefits. Further, many power utilities do not currently have a market structure that rewards the adoption of stabilizing technologies with renewable sources. The enormous growth of renewable sources has been relatively sudden and unexpected. Some system operators are currently working on providing market value for these ancillary services. However, currently such services do not exist in most markets.

The second challenge is overcoming barriers involving policy/standards for integrating renewables. Most existing standards do not see the need for adding grid forming resources. Power system operators are still investigating the adoption of these sources. Due to the lack of commercial products that use this technology, the power system operators do not have a well justified approach for studying such technologies. On the other side, inverter manufacturers do not want to invest in technologies that do not have a well-defined path to commercialization. Without an established standard for this technology, these inverter manufacturers would have to take significant risk in investing in such technologies. The US Department of Energy has recognized the challenge with such technologies and is investing resources into researching these technologies. Hopefully, grid forming inverters will play a huge role in stabilizing future power systems!

1.6 References

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