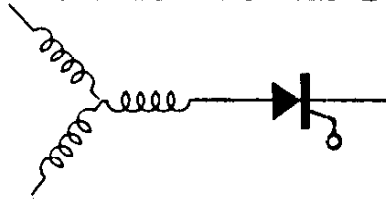




WEMPEC



Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
84-4

Variable Speed Generator Technology Options
for Wind Turbine Generators

T.A. Lipo
University of Wisconsin
Madison, Wisconsin

Department of Electrical and Computer Engineering
University of Wisconsin-Madison
Madison, Wisconsin 53706

June 1984

VARIABLE SPEED GENERATOR TECHNOLOGY OPTIONS FOR WIND TURBINE GENERATORS

T.A. Lipo
 Department of Electrical and Computer Engineering
 University of Wisconsin
 Madison, Wisconsin

ABSTRACT

The electrical system options for variable speed operation of a wind turbine generator is treated in this paper. The key operating characteristics of each system are discussed and the major advantages and disadvantages of each are identified.

INTRODUCTION

Adjustable speed operation of AC motors by use of frequency converters is making rapid inroads in the DC drive market. On the other hand, the concept of variable speed as applied to power generation rather than power utilization has, except for several prototype systems, not been widely exploited. The rapid development of AC adjustable speed drives has, however, resulted in an array of alternatives which also have potential application for variable speed power generation. This paper will focus on the options available for variable speed wind turbine generators (WTGs) together with the advantages and disadvantages of each. In particular, potential configurations for large wind turbine generators rated above 1 MW are emphasized.

CANDIDATE VARIABLE SPEED SYSTEMS FOR LARGE WIND TURBINE GENERATORS

The field of adjustable speed machine systems is an active and growing discipline such that a completely comprehensive treatment of technology options is an extremely difficult task. In particular the number of feasible options appears to vary inversely with the power rating of the WTG. This paper will be concerned primarily with identifying major technology options primarily at WTGs rated above 1 MW. A less comprehensive assessment of technology options for lower power WTGs are summarized in the second portion of this paper.

DC Generator with Line Commutated Inverter Bridge

Probably the most straightforward variable speed system for a WTG utilizes a DC generator with inversion of the generated DC power to AC by use of a line commutated rectifier bridge as shown in Fig. 1. Current flow is in 120° blocks at line frequency on the AC side of the inverter and filtering at the AC terminals of the bridge is needed to suppress harmonic current flow into the power system and to correct the power factor to unity. Because of the heavy filtering required to eliminate unwanted harmonics of the simple six pulse bridge of Fig. 1, other bridge configurations are also in common use. For example, the dual six pulse bridge arrangement of Fig. 2 results in the elimination of the lowest frequencies, the 5th and 7th harmonic components inherent in the bridge configuration of Fig. 1 while halving the next lowest components, the 11th

and 13th. An advantage of the dual bridge configuration of Fig. 2 is that each bridge need only be rated at one-half the KVA rating of the single bridge of Fig. 1. It should be mentioned that such alternatives are generic to any of the systems to be discussed which utilize six pulse bridge configurations.

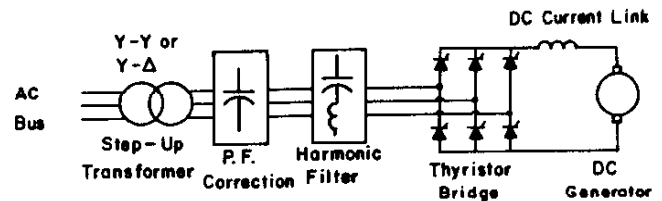


Fig. 1 DC Generator with DC Current Link and DC/AC Inverter.

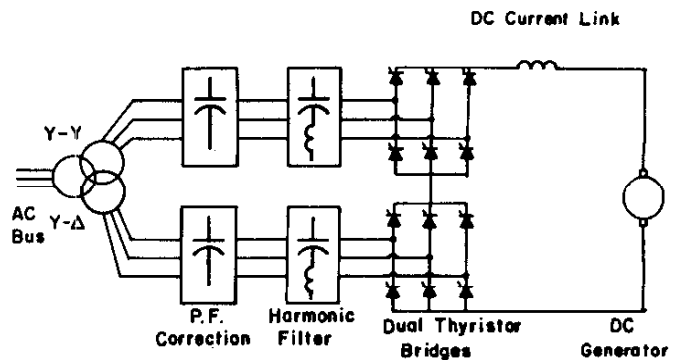


Fig. 2 DC Generator with DC Current Link and Dual DC/AC Inverters.

While not strictly necessary, some filtering of the DC voltage of the bridge is typically employed so as to minimize stray losses in the generator due to harmonic currents. The simplest type of filter is to simply use a DC link inductor as shown in Fig 1 to smooth the current. Such systems are said to utilize a DC current link and when the size of the inductor is large, the converter/generator system operates much like a current source. An alternative to the filtering problem is the placement of a capacitor across the terminals of the machine and employ a much smaller link inductor which is now selected primarily to limit charging current into the capacitor as shown in Fig. 3. In this case the current flow from the machine is smoothed by providing a low impedance path to harmonic currents. Such a configuration is said to employ a DC voltage link

arriving from the converter. When the capacitance is large the converter/generator system appears much like a voltage source to the power system.

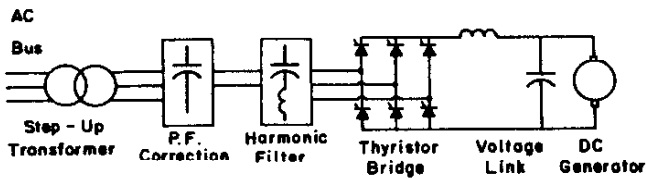


Fig. 3 DC Generator with DC Voltage Link and DC/AC Inverter.

It is well known that the power factor of a line-commutated bridge varies in direct proportion to the ratio of DC to AC voltage. Hence, in order to maintain good power factor at the terminals of the bridge, the inverter must be controlled such that the voltage on the DC side of the bridge must be maintained constant near its maximum permissible value. In converter terminology such a control is usually called constant extinction angle control in which the inverter is commutated such that the inverter thyristors have just sufficient time to recover blocking ability before forward voltage is reapplied.

Operation of the DC generator at a variable speed, however, implies a variable DC voltage since the internal generated EMF of the machine varies directly proportional to speed. If the speed range of the WTG is small (10 to 15%) the DC side voltage can be maintained at its rated value, however, by simply increasing the field excitation of the DC generator as speed decreases. Such a control strategy implies a slight overdesign of the generator in order to overflux the machine and accommodate the extra field heating. Alternatively, for larger speed ranges the DC voltage at the inverter terminals must be reduced to match the varying DC generator voltage by control of the inverter extinction angle. Since the system power factor would then vary, such a control would imply a larger capacitor bank for power factor correction.

Special advantages of this system include:

1) Minimal Torque Pulsations. Since the generator is DC rather than AC the torque pulsations associated with harmonic currents due to switching of the machine side converter is eliminated. Some residual torque pulsations will remain depending upon the degree of DC side filtering. However, the frequency of these pulsations are 360 Hz and multiples of 360 Hz which are unlikely to cause resonance problems.

2) Straightforward Control Algorithm. Whereas the control of AC machines in a variable speed application often becomes rather complex, the corresponding control of a DC machine is simplicity itself and is a long established technology.

Several unique disadvantages which could influence application of this system to a WTG application are:

1) Maintenance and Reliability Concerns. The shortcomings of DC machines in these important categories have been long cited, perhaps overly so. Since most WTG installations do not require continuous operation, brush and commutator maintenance should not be particularly difficult. However, reliability questions concerning a large mechanically commutated machine in the environment of a WTG remain to be resolved.

2) DC Fault Protection. This system shares with most other configurations the advantages of quickly isolating the machine from the AC system. Rapid control of the

converter bridge can prevent fault current contributions from the DC machine when faults occur on the AC side of the converter. However, rapid interruption of faults on the machine side of the converter necessitates a DC breaker which is more expensive and requires more maintenance than an AC breaker.

3) Control Response Limitations. One of the potential advantages of variable speed systems over constant speed systems is the potential ability to damp torsional oscillations of the WTG. Such an application would however, require torque control over a wide bandwidth. In comparison to many AC systems which will be discussed, the speed of response of the system of Fig. 1 is relatively slow since torque control is accomplished by adjustment of the field current. The inherently large field time constant would be difficult to overcome if rapid changes in torque were necessary.

Problems involved with rapid control of torque could clearly be avoided with armature control. However, since power factor is an important consideration, modulation of the voltage of the converter bridge of Fig. 1 would probably be impractical. Use of a chopper intermediate stage would accomplish this task but such a force commutated device is considered as impractical for WTGs of large kilowatt rating. Such configurations are more suitable for lower power applications which will be addressed later.

Synchronous Generator with Thyristor Rectifier and Inverter

Another class of system suitable for wind power generation is a synchronous generator supplying power through a DC current link rectifier/inverter as illustrated in Fig. 4. Commutation of the line side inverter is again accomplished by taking VARs from the power system. Commutation of the machine side converter is provided by taking VARs from the synchronous machine. In this case, excitation of the machine is by means of a brushless exciter.

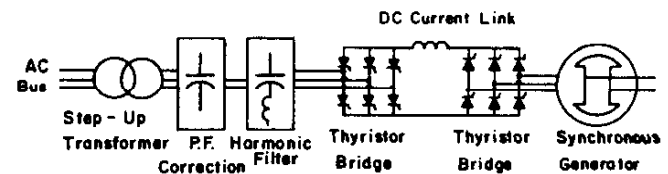


Fig. 4 Synchronous Generator with DC Current Link and DC/AC Inverter.

Electrical generated power must pass through the rectifier/inverter so that the converters must be rated at the full machine rating. In this case 120° blocks of current flow on the AC sides of both the rectifier and inverter. Again, the harmonic content on either the machine side or utility side converters can be reduced by more elaborate bridge configurations. In particular, the synchronous generator is frequently wound as dual three phase winding groups wherein each group feeds six pulse bridges in much the same manner as Fig. 2. If the speed range is again narrow (10-15%) the line side inverter can be maintained at its minimum extinction angle by adjusting the field current of the synchronous generator with speed in much the same manner as for the DC generator.

Important special advantages of this system include:

1) Wide Speed Range. In general, the switching frequency of the machine side converters is limited by the subtransient reactance of the machine. With typical per unit numbers, frequencies of 150-200 Hz are readily

obtainable.

2) High Frequency Torque Pulsations. The torque pulsations are again multiples of six times the frequency of the machine side converter. Since a typical frequency range of the machine side inverter in a wind power application is 30-90 Hz the torque pulsations will range from 180 to 540 Hz, which is comfortably above the measured resonances of the wind generator.

3) Strong Electrical Damping. Again strong damping of mechanical oscillations can be initiated from the machine side of the mechanical system. Since the frequency range of the rectifier is relatively high (30-90 Hz), effective control of oscillations can be maintained over the speed range.

4) Rapid Reclosure After a Fault. Upon a line interruption following a fault, the inverter is isolated from the line and hence the commutation energy to switch the inverter is lost. However, the current flow in the DC link can be maintained as circulating current by simultaneous firing of a thyristor in the top and bottom of the inverter bridge. Upon clearing of the fault, current can be rapidly established on the AC side of the converter by suitable control.

This system has a number of potential disadvantages among which are:

1) Low Frequency Torque Pulsations Near Synchronous Speed. The DC side ripple harmonics of the bus side converter is fixed at 300 Hz whereas the ripple DC link harmonics of the machine side converter are six times the inverter frequency. When the machine approaches synchronous speed the superposition of the two frequencies in the DC link can produce sum and difference "beating" frequencies. Since these beat frequencies pass into the machine, torque harmonics much lower than that produced by either converter operating independently can arise. These currents can produce torques which resonate with the mechanical system. This beating effect can be minimized with proper selection of the DC link reactor and control of the machine side converter.

2) High Harmonic Distortion. Again the current on the AC side of the converter set is comprised of 120° blocks. These quasi-rectangular currents are relatively large since the converter is rated at full rated power of the generator. The harmonic content injected into the power system can again be reduced with the more elaborate bridge configuration of Fig. 2.

If controlled starting as a motor is not required, it is possible to replace the machine side thyristor converter by a simple diode bridge. Torque control of the machine must now be accomplished by field control. Response of the system is similar to the DC system of Fig. 1 and rapid control of the armature current is sacrificed.

Doubly Fed Induction Generator with DC Current Link Rectifier and Inverter

Another type of system which bears a great similarity to the synchronous generator scheme of Fig. 4 is the doubly fed induction generator of Fig. 5. The system again uses a rectifier/inverter with a DC current link wherein the machine side converter is connected to three phase rotor windings by means of slip rings. Current flow is in 120° blocks at slip frequency on the AC side of the rotor connected converter and 60 Hz on the AC side of the stator connected converter.

In principle, operation either above or below synchronous speed is possible. Synchronous speed in this case is defined as the point at which the rotor rotates synchronously with respect to the stator rotating MMF when the slip rings are shorted. When the machine generates power below synchronous speed, power is supplied to the utility

from the stator windings. However, power must still be supplied to the rotor windings of the machine through the slip rings. The power required is essentially proportional to the difference between rotor speed and rotor synchronous speed (slip frequency) times rated power. Hence, if the speed range is limited the rectifier/inverter need only be rated for a fraction of rated power (slip power). It can be noted from Fig. 5 that in this mode of operation the rotor side converter operates as a variable frequency inverter. Conversely, when the machine generates power above synchronous speed, electrical power is also extracted from the rotor via the slip rings. Again the converters need have a rating equal only to slip power. The rotor side converter operates in this case as a rectifier.

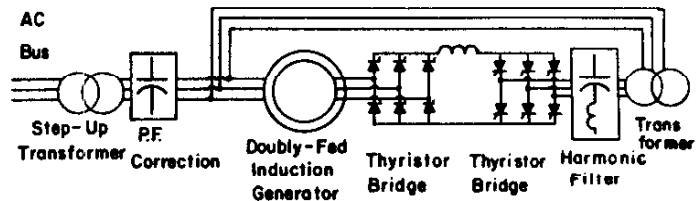


Fig. 5 Doubly Fed Induction Generator with DC Current Link and AC/DC/AC Rectifier-Inverter.

In addition to the usual step down transformer from the distribution voltage level, another transformer is typically provided to match the voltage level of the rotor windings to that of the stator. This transformer provides additional short circuit protection and helps reduce the ripple current content in the DC link. The turns ratio is usually selected so that the extinction angle of the inverter and retard angle of the rectifier are at their minimum values when the machine operates at maximum slip frequency.

Among the particular advantages of this system are:

1) Converter Ratings Based on Slip Power. As noted above the converters need be rated only at a fraction of rated power. For example, if the expected speed range is 10-15% then the converters need be rated only at 0.1-0.15 per unit power.

2) Control Response. Since the rotor connected bridge must control power at slip frequency the response of this system is not expected to be as good as the synchronous motor system of Fig. 4. Nonetheless, the response can be markedly improved compared with the DC generator configuration of Fig. 1.

3) Harmonics. Since the bridges handle only slip power, the corresponding current harmonics are also proportional to slip power and are more easily filtered than previous systems.

4) VAR Control. While the VAR requirements of this system are always positive (lagging VARs), a certain amount of VAR control is possible by coordinating the control angles of the rectifier and inverter. Hence, unity power factor operation could be achieved continuously with a fixed capacitor bank without the need for switching capacitors.

This system has several particular drawbacks including:

1) Restricted Speed Range. From the above discussion it is apparent that the power flow into the rotor reverses direction as the machine passes through synchronous speed. As a result, the rotor side bridge loses commutation energy and a "dead spot" exists in which control is lost. One possible solution to this problem is to provide forced commutation capability for the rotor side bridge. A number of such forced commutation circuits are possible

but a particularly simple arrangement is shown in Fig. 6. Since forced commutation is only required near synchronous speed, the size of the commutation capacitor would not be substantial. Note however that since the circuit utilizes the neutral connection of the rotor an extra slip ring must be provided.

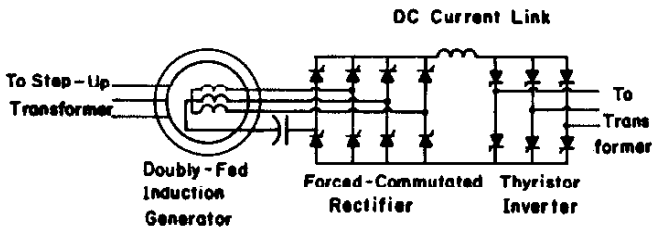


Fig. 6 Doubly Fed Induction Generator Arrangement with Force-Commutated Rectifier.

Another solution to the loss of control problem is to simply operate the system only above or below synchronous speed. Continuous operation above synchronous speed appears to be the preferred strategy due to the difficulty in operating with a bridge in the variable frequency inversion mode and the size penalties involved in operating an electrical machine below rather than above its nominal rated speed.

2) Torque Pulsations. The rectangular currents which flow in the rotor windings result in 5^{th} , 7^{th} , 11^{th} , 13^{th} , ... harmonics of slip frequency. These harmonic currents in turn interact with the fundamental component to produce electromagnetic torque pulsations at the 6^{th} , 12^{th} , 18^{th} , ... harmonics of slip frequency. Since the slip frequency spans the range from near zero to, say 20 Hz, the sixth harmonic torque pulsation would vary from zero to 120 Hz. Although the amplitude of these pulsations is rather small, large amplification can occur at the mechanical resonant frequencies. It has been shown that by modulating the DC link current the amplitude of these pulsating torques can be reduced by a factor of ten [1]. Resilient couplings, for example a Holset coupling, can be used to reduce the amplitude of these injected torques to a manageable value. Nonetheless, the difficulty of torque pulsations appears to be a major disadvantage of this system.

3) Slip Rings. Presence of slip rings implies a potential maintenance issue which is not present with the synchronous generator scheme. Since the rotor current flows in 120° blocks the current in a given phase is zero over 60° intervals and these intervals can be substantial at low slip frequency. It is well known that rapid brush wear can occur under zero current conditions but the severity of the problem under discontinuous operation with a converter is apparently not well understood. Also, without careful design the quasi-rectangular currents can induce currents in the rotor body itself which could, potentially, cause deterioration of the rotor bearings. Both effects are potential concerns which need to be addressed.

4) Lagging Power Factor. Since both the rectifier and inverter must absorb VARs to effect commutation, the overall power factor of this system cannot be raised to unity. A relatively substantial bank of power factor correcting capacitors would be required to supply the VAR need of both the induction generator as well as the converters.

As was the case for the synchronous generator configuration, the thyristor bridge (rotor connected bridge in the case of super synchronous operation) can be replaced by a simple diode bridge. Control of rotor power

is maintained by means of the firing angle of the inverter bridge. However, the possibility of starting the machine as a motor is again lost. The VAR input into the system cannot be adjusted since the inverter control must be dedicated to control of power.

Doubly Fed Induction Generator with DC Voltage Link Rectifier and Inverter

Whereas DC current link converter configurations derive commutation volt-amperes from the connected supply, DC voltage link systems typically (but not inevitably) rely on commutation energy from special purpose capacitor circuits or by means of self commutating switches (transistors or GTOs). Such converters are inherently more expensive than DC current link converters. However, costs of these converters are decreasing rapidly with the development of new high power transistor and gate turn-off (GTO) switches. If the desired speed range is small the rotor connected converters need only handle a small fraction of rated power and the possibility of using a DC voltage link may be practical. Such a voltage link configuration is shown in Fig. 7 in which the rotor connected converter is operated in forced commutation while the stator connected converter commutates naturally. Other arrangements are possible in which the stator side converter (or both) are force commutated.

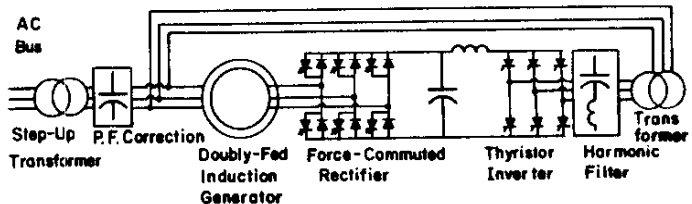


Fig. 7 Doubly Fed Induction Generator with DC Voltage Link and Force-Commutated Rectifier.

In general, forced commutated converters can be operated in either of two modes. In the six step mode the converter switches are triggered at the lowest possible rate to ensure a desired output frequency. In this case the converter AC side line voltage assumes a quasi-rectangular waveshape of 120° voltage blocks which, in effect, forms the dual of the DC link converter. Harmonic voltages of 5, 7, 11, 13, ... times the fundamental are produced which, in turn, induce currents of these frequencies in the corresponding AC current. In the pulse-width-modulated or PWM mode the switching frequency is modulated so as to eliminate these undesirable harmonics. The switching frequency is sufficiently high that harmonic torques which would be of concern in a wind turbine generator application are effectively eliminated. The presence of harmonics plus the large DC filter requirements of the six step mode suggests that PWM operation would be the preferred triggering scheme for this application.

Special advantages of a voltage link system are:

1) Smooth Transition Through Synchronous Speed.

Since commutation of the rotor side converter is now provided internally, the problem of "dead spots" near synchronous speed is eliminated. Control gains remain high throughout a wide speed range including synchronous speed so that strong damping of mechanical oscillations is always possible.

2) High Frequency Torque Pulsations Only. In general, the frequency of a PWM inverter is readily raised to the point where the resulting torque harmonics are well above the resonant frequencies of the mechanical system.

3) Smaller Per Unit Rating than Equivalent DC Current Link System. Since a PWM converter is equally capable of rectifying or inverting, operation of the generator above or below synchronous speed is possible. Hence, for a given variation in power from maximum to minimum speed, the rating of the PWM converter need be rated only at the difference between maximum and minimum power suggesting a slight saving in rating of the DC voltage link system compared to the DC current link.

4) VAR Control. Since the force commutated converter does not require VARs for successful operation it can actually supply VARs to the Generator thereby permitting the control of VARs as well as power. Operation of the system at unity or leading power factor appears possible with proper attention to the rating of the converters.

Important disadvantages of this system are:

1) Cost. There is a cost penalty for this system due to the requirements of high grade switches and/or extra components needed to accomplish forced commutation. However, the cost of such converters are rapidly dropping due to the emergence of new high power transistors and GTOs. Of all the configurations under consideration this system is perhaps the most dependent on emerging technology.

2) Complexity. Successful implementation of PWM schemes typically require a considerably more complicated voltage control algorithm which invites questions concerning reliability. Operation of the PWM converter both above and below synchronous speed implies an extra diode bridge to supply power during subsynchronous operation (shown in Fig. 8).

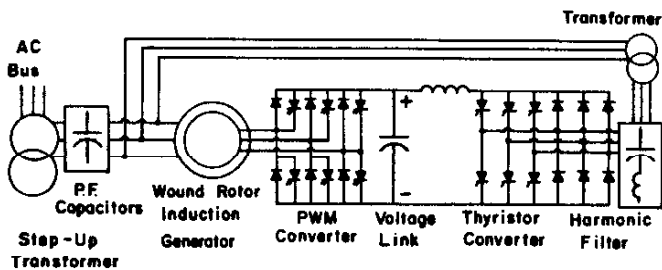


Fig. 8 Doubly Fed Induction Generator Scheme Capable of Operation Above and Below Synchronous Speed.

Doubly Fed Induction Generator and Cycloconverter

An alternative to DC current or voltage link systems is the cycloconverter configuration of Fig. 9. The cycloconverter is a device which transforms line frequency power to adjustable frequency power directly without use of an intermediate DC link. Numerous cycloconverter configurations have been proposed but the 36 thyristor arrangement shown in Fig. 9 is most widely used. This type of converter operates essentially as a voltage source. The cycloconverter is effectively a sampling type of converter where the input frequency is fixed and the sampling frequency changes with output frequency. In order to construct an output waveform, samples are taken from the three phase input. With proper modulation of the cycloconverter the current is nearly sinusoidal with superimposed harmonics related line frequency and to the switching frequency of the cycloconverter bridges. Because of the limits imposed by the sampling theorem, the output becomes progressively distorted as the output frequency is increased with about 1/2 the input frequency being the maximum obtainable with a 36 thyristor configuration.

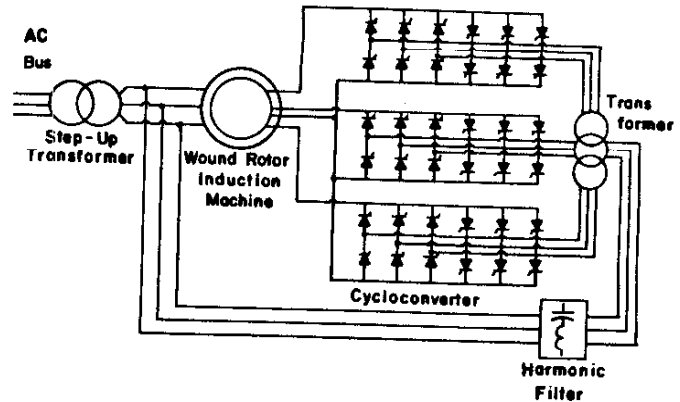


Fig. 9 Doubly Fed Induction Generator with Direct AC/AC Conversion.

As was the case for current and voltage DC link system, numerous types of cycloconverters are useful. For example, an 18 thyristor voltage source system can be employed. In this case the useful frequency range is limited to about 1/3 the input frequency. Current source cycloconverters are also in use. Such a cycloconverter is often called a "hidden link" cycloconverter since the current source mechanism is obtained by use of an AC inductor on the input side of the cycloconverter.

Since isolation is needed to prevent short circuits, cycloconverters are generally accompanied by an input transformer with three isolated secondaries. The turns ratio is selected to provide maximum output voltage under the highest slip power condition. In principle, the transformer could be omitted if the three rotor phases of the machine were isolated. However, this option is not considered practical for a WTG as it would require six slip rings rather than three.

The most pertinent special advantages of the cycloconverter fed, doubly fed induction generator scheme appear to be:

1) Power Factor Control. With proper control of the voltage applied to the rotor of the machine, the VARs consumed or supplied by the machine can be adjusted at will. In particular, by proper adjustment the VARs required to provide switching of the cycloconverter can be obtained from the stator of the machine itself so that the entire system is "self-supporting" and the machine is capable of supplying power at unity power factor.

2) Smooth Transition Through Synchronous Speed. This configuration shares with the PWM DC voltage link the capability of continuous operation at synchronous speed. The "dead zone" inherent in naturally commutated DC current link converter systems is not present in this arrangement. The WTG application appears to be a good match for the inherent performance capabilities of the cycloconverter since the speed range of the WTG is relatively narrow, requiring only a limited range of output frequencies from the cycloconverter. Since commutation takes place at a fixed rate (360 Hz), good control of the rotor current is maintained down to DC frequency so that damping of torsional oscillations can be provided even when the output frequency is near (or at) zero.

Several important drawbacks exist for this scheme which restrict somewhat its usefulness. They are:

1) Torque Pulsations. In general, harmonic torques produced by the switching of the cycloconverter are not of concern since the predominant frequencies are integer multiples of 360 Hz, which are well above the resonant fre-

quencies of the mechanical system. However, because the switching of the cycloconverter is not synchronously tied to the output frequency, harmonic components of the output are not rigorously tied to the fundamental frequency of the input. Low frequency torque pulsations could arise which may induce mechanical oscillations. In particular, a "beating" phenomenon occurs when the frequency approaches integer fractions of 60 Hz (2,3,6,10,12,15,... Hz). Amplitude of these pulsations are very small for high integer ratios of input to output frequencies (30:1, 20:1, etc.) but may become appreciable at lower ratios (4:1, 3:1 and 2:1). The most severe (2:1 and 3:1) can be avoided by restricting the frequency output (rotor slip frequency) to less than 20 Hz. The next most severe conditions for a WTG application are the 12 and 15 Hz cases which would have to be carefully examined.

2) Harmonic Structure of the Injected Line Currents. One property which distinguishes the cycloconverter from the DC voltage or current link system is that the harmonic structure of the voltage output is not an easily predictable function. Harmonics are dependent not only upon the input frequency and switching instant but also upon the impedance presented to the cycloconverter during commutation (switching of the cycloconverter thyristors). Due to the asynchronous tie between input and output the harmonic structure of the output spans a frequency band rather than consisting of discrete harmonic components of the input. As a result the filtering problem is somewhat more complicated. Since tuned filters are inappropriate, a low pass filter must be used which implies heavy filtering requirements.

3) Behavior During Single Phase Line Fault. In general, buffering of the machine from the utility by means of a converter provides an inherent benefit in the event of system faults since the line side converter can be rapidly controlled to greatly reduce the fault contribution from the wind turbine generator. However, the characteristic of a single phase fault or single phase open circuit is particularly difficult for cycloconverter systems since large harmonic components including fundamental components of the line frequency are admitted into the output (i.e. appear on the rotor side of the cycloconverter) upon a single phase fault. Whereas six pulse converter bridge schemes can be equipped to handle such occurrences, a cycloconverter fed machine would probably require switching off the line resulting in a reliability concern relative to other alternatives.

Cycloconverters can also potentially replace the dual converter bridge of a synchronous generator system (Fig. 4). However, because the ratio of input to output frequency is restricted, such an application would imply that the frequency of the generator would have to be kept relatively low (below 15 Hz) or relatively high (above 360 Hz) to provide for low harmonic distortion. Operation at such low or high frequencies would probably seriously restrict the design of the synchronous generator. Also, since full rated power must now pass through the cycloconverter, severe filtering problems would occur. Finally, serious power factor correction problems would also arise, particularly for the low frequency option in which commutating VARs are required from the utility side to provide commutation energy for the cycloconverter.

VARIABLE SPEED OPTIONS FOR SMALLER WIND TURBINE GENERATORS

As the rating of the WTG is reduced the number of alternatives is enlarged. All of the previously mentioned schemes remain practical for lower power applications. However, in general, the per unit costs of wound field

machines such as the synchronous and wound rotor induction generator increase as ratings of such systems decrease, thereby permitting various DC and cage rotor induction generator configurations utilizing force commutation to become more competitive. If variable speed systems which require connection to passive loads rather than the utility grid are not considered, the following additional systems can be identified.

DC Generator with Chopper Based DC Voltage Link

Figure 10 shows a DC WTG scheme in which the generator is buffered from the output by a DC voltage link formed by a step down chopper. The voltage on the output side of the chopper (utility side) can be maintained constant by pulse width modulation of the chopper. Hence, the inverter bridge can be maintained at its minimum extinction angle over a wide variation in generator speed. Step up chopper arrangements are also possible in which the varying generator DC voltage is increased through the chopper to a higher constant level. Again current in the utility side inverter flows in 120° blocks. Filtering requirements can again be relaxed by resorting to more complex converter configurations (Fig. 2).

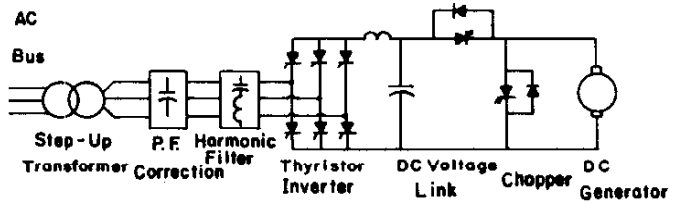


Fig. 10 DC Generator with 2 Quadrant DC/DC Step Up Chopper.

Induction Generator with DC Voltage Link

An AC alternative the chopper/DC generator is the DC voltage link system of Fig. 11 utilizing a PWM inverter together with a squirrel cage type induction generator. Again, the DC link voltage can be maintained constant by pulse width modulation of the machine side converter. Because such an induction generator requires lagging VARs, the converter must be force commutated. The utility side converter can again be controlled for best power factor operation (minimum extinction angle) necessitating only a minimal amount of power factor correction. The above comments concerning filtering again apply.

Operation of the machine side converter in the "six step" mode is again possible. However, since the level of excitation of a squirrel cage machine cannot be controlled by independent means as for the other machine types the DC link voltage will necessarily change in direct proportion to frequency. Since the DC link voltage cannot be maintained as constant, the utility side inverter control angle must be adjusted continuously so accommodate this variation. Hence, the power factor of the converter can not be kept constant but changes with control angle.

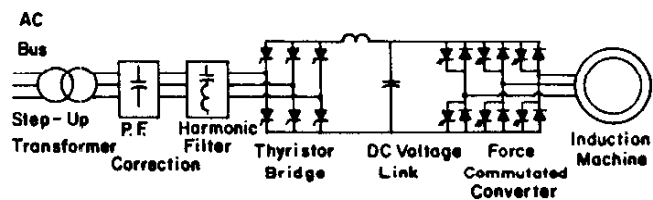


Fig. 11 Induction Generator with DC Voltage Link and AC/DC/AC Conversion.

Induction Generator with DC Current Link

Another induction generator alternative incorporates the use of a DC current link rather than a voltage link. However, since excitation of the generator must again be provided by the machine side converter, forced commutation is needed. Figure 12 shows such a configuration utilizing an auto-sequential type of commutation scheme (ASC inverter). One problem which appears to be inherent in the operation of this system is that the DC side voltage varies widely with load and approaches zero when the machine is unloaded. As a result, the line side converter control angle varies widely resulting in a difficult power factor correction problem on the utility side of the converter.

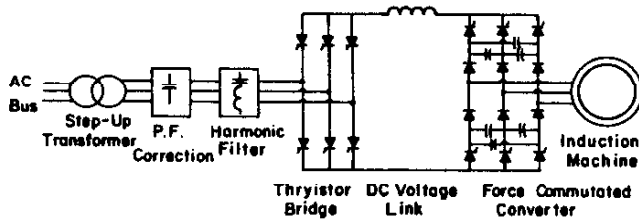


Fig. 12 Induction Generator with DC Current Link and AC/DC/AC Conversion.

Induction Generator with Cycloconverter

The cycloconverter forms the third class of converter which has been discussed and, indeed, as was the case for doubly fed induction generator and synchronous generators, this type of converter can also be utilized with a squirrel cage type of induction generator. However, in this case the generator frequency must be kept at a fraction of line frequency (60 Hz). VARs must be supplied both to commutate the cycloconverter and magnetize the induction generator and the numerous disadvantages appear to outweigh the benefits in this application.

Induction Generator with High Frequency Link Converter

One type of converter which has not been discussed heretofore is the high frequency link type of converter, as shown in idealized form in Fig. 13. In essence, this type of converter is a double ended cycloconverter which utilizes resonant type of commutation to step up the input frequency to a large value (10 KHz or more). Another cycloconverter is used to then reduce the link frequency power to a low value (for example 60 Hz). Numerous types of high frequency links have been proposed [2,3]. Such converters are in a less developed stage than other circuits and many important question need to be resolved. For example, it is not known definitively whether excitation of a squirrel cage induction generator is possible with such a converter without power factor correcting capacitors. The questions concerning power factor and the degree of harmonic filtering needed to interface with a utility system have yet to be addressed. One major disadvantage of such schemes is the high device count which can number 72 thyristors or more, prompting questions concerning reliability. The inherent advantage of these circuits, namely low weight and compactness do not appear to be relevant in a WTG application.

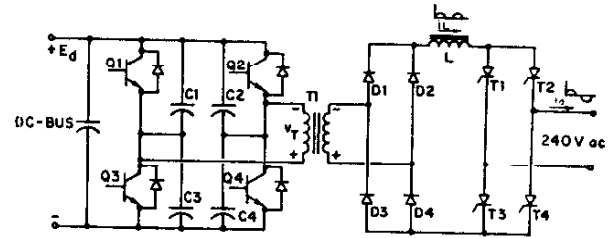


Fig. 13 High Frequency Link Self-Commutated Inverter (One Phase).

Permanent Magnet Generator Configurations

When ratings reach 10-20 Kw and less, the complexity of the choices for variable speed operation again becomes enlarged. In particular, such application ratings become amenable to the use of permanent magnet generators. Dual systems to those discussed for synchronous and induction generators (Figs. 4 and 11-13) become potential candidates to be examined. The key difference between permanent magnet generators and more conventional synchronous generators is the lack of an independently controllable excitation winding. Hence, the generator terminal voltage varies with speed necessitating control of the line side converter. As a result, power factor will change under varying load conditions.

CONCLUSION

The electrical systems options for variable speed operation of a wind turbine generator are extensive and may even be increasing as a result of emerging high power transistors and GTOs. This paper has presented a summary of the technology options and trade-offs between alternatives for variable speed electrical generating systems as applied to a wind turbine generator. The paper should help clarify some of the major issues involved in this application and assist in the selection of the proper technology.

REFERENCES

1. T.A. Lipo, "Analysis and Control of Torque Pulsations in Current Fed Induction Motor Drives", *Electric Machines and Electromechanics*, Vol. 3, April-June 1979, pp. 357-368.
2. P.M. Espelage and B.K. Bose, "High-Frequency Link Power Conversion", *IEEE Trans. on Industry Applications*, Vol. IA-13, No. 5, Sept./Oct. 1977, pp. 387-394.
3. F. Schwartz, "A Doublesided Cycloconverter", *IEEE Trans. on Industrial Electronics and Control Instrumentation*, Vol. IECI-28, No. 4, November 1981, pp. 282-291.