

DC Microgrid and Control System
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Lecture - 09
Power Electronic Converters in Microgrid Applications
(Power Electronic for Interfacing)

Welcome to our lectures on DC microgrid and today we shall discuss about the power electronics converter in microgrid applications. So this will be our presentation layout.

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Contents

- Power Converters Interfacing Applications
- AC to DC Converters (Rectifier)
- Pulse Width Modulation (PWM) Voltage Source Converters
Three-phase PWM Voltage Source Converter
- Multilevel Converters
- Multilevel Converter Topologies

That is power electronics converter interfacing applications, AC to DC converter which we have seen so many places. There will be a AC to DC converter. Essentially it can be controlled or uncontrolled rectifier. Pulse width modulation technique for the voltage source converter, three-phase PWM voltage source converter. Thereafter multilevel converter and its topologies. These will be our course content today.

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Power Converters Interfacing Applications

- In a DC micro grid system, it is very important to analyze how electrical power flows between AC and DC networks.
- The smart DC grid systems can be designed based on bidirectional power flow in which electrical energy generated by some RES such as PV panel or fuel cells can be transferred back to the AC grid to support the AC grid.
- Thus in order to analyze the interface issues between the AC and the DC grids, different AC-DC topologies can be considered.

So in a DC microgrid system it is very important to analyze how electric power flows between AC and DC network. So we have to see that So there will be the interconnectivity between AC and DC and our power flows. The smart DC grid system can be designed based on bidirectional flow in which electrical energy generated by some RES such as PV panel or fuel cell can be transferred back to the AC grid to support the AC grid. So this is we require to understand.

If there is excess of power, then power can flow back DC grid to AC grid or the main utility grid and power may come when there is a power deficiency of the DC microgrid from the main grid. Thus in order to analyze the interface issues between the AC and the DC grids, different AC to DC topologies can be considered and it will be discussed now.

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AC to DC Converters (Rectifier)

- As shown in Fig. 1 ac-dc converters can be classified between topologies working with low switching frequency (line commutated) converter and other circuits which operate with high switching frequency.

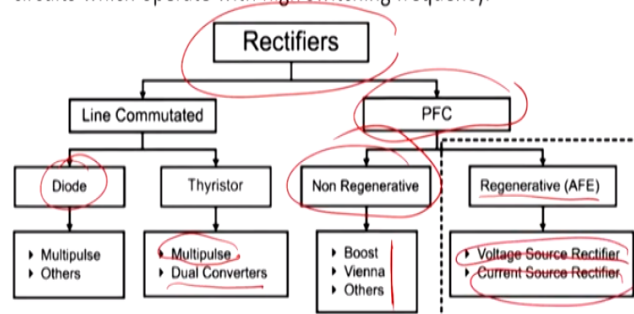


Fig.1: Classification of Rectifiers

So this is overall AC to DC converter and rectifier and this is a figure 1 of AC to DC

converter can be classified between that apologies working on low switching frequency. These are line commutated. These are mainly thyristor driven converter and other circuits will operate at the high switching frequency like IGBT and maybe the phosphate of silicon carbide. So this is a rectifier.

Ultimately, if it is a line commutated, if it is uncontrolled, then you may have a diode, but considering the THD you may have a multipulse converter that is actually you play around with your transformer. You have 6 pulse transformer, you have 12 pulse transformer, and accordingly THD will go down. Students are requested to see my courses on the Advanced Power Electronics that aspects multipulse converter has been discussed in details. Same way it can be controlled then it is thyristor based.

And so it is the multipulse converter. Same thing it is just controlled and thereafter we can have a dual converter AC to DC and DC to AC, both the conversion are possible. And another can be your power factor corrected entry point so that you do not inject power quality issues like problem of the THD into the system and it can be classified in the two categories.

One is one directional power flow that when power flows from the AC side to DC side and that is called the regenerative and their boost Vienna and other topologies are possible. And otherwise you may have a 3 phase case you have a regenerative kind of thing. So bidirectional power flow is possible AC to DC and DC to AC. Then it is active rectifier and it can be voltage source rectifier or the current source rectifier. So overall this is the classification.

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AC to DC Converters (cont...)

- The simplest line-commutated converters uses diode to transform the electrical energy from ac to dc.
- The use of thyristors allows for the control of energy flow. The main disadvantage of these naturally commutated converters is the generation of harmonics and reactive power.
- Harmonics have a negative effect on the operation of the electrical system and attention should be given to their generation and control.
- It is clear that the line currents of line commutated converters (example shown in Fig.2) are distorted by significant low order harmonics.

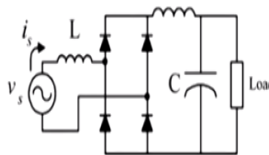


Fig.2: Single-phase Rectifier Circuit

Now you have studied into the power electronics courses. It is just a revision. A simplest line commutated converter used direct to transform electrical energy to AC to DC. The

use of thyristor allows for the controlled energy flow so you can control the thyristor angle. The main disadvantage of this naturally commutated converter are the generation of the harmonics and the reactive power.

So you cannot have a control over reactive power generations. So if you actually change the thyristor angle you have a displacement power factor and thus your power factor get distorted and reduced. And as well as since it is a nonlinear change, you inject harmonics into the AC system. Harmonics have a negative effect on the operation of the electrical system and attention should be to their generation and control.

So we can have a different kind of technique which we have already discussed in my previous lectures in advance power electronics and control, that is SHE that is called selective harmonic elimination. You can look at that video lecture and there you can see that how this THD can be reduced. It is clear that the line current of the line commutated converter, it will be shown in the next figure is distorted significantly with a lower order harmonics.

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AC to DC Converters (cont...)

- Thus passive filters can be applied in the DC-link or at the front end of the converter to improve the quality of line currents.
- Another conceptually different way of reducing harmonics to use single-phase or three-phase PWM Rectifier or power-factor correction (PFC) converters.
- The most common one is a single phase system, based on a diode rectifier with a boost converter at the DC link side (Fig. 3 (a)).

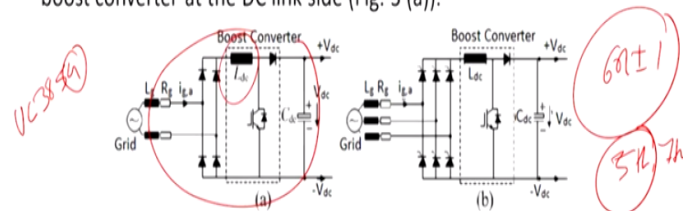


Fig.3: Different AC-DC topologies: (a) single-phase PFC, (b) three-phase

Generally, if you have a three phase three wire system your harmonic content will be $6n \pm 1$ that means fifth, seventh are the dominating harmonics and so on. Thus the passive filter can be applied to the DC link or at the front or the front end of the converter to improve the quality of the line currents or you can have a selective harmonic eliminations.

If you have this thyristor control you can eliminate only one frequency because you can only have a control over turn on, but if it is a GTO and other full control switches, so multiple harmonics can be eliminated by SHOULD. Another conceptually different way of reducing harmonics to use single phase or three phase PWM rectifier or power factor

correction converter.

So you will see that boost topology and ultimately we require to take the voltage envelope and current is being forced to remain into the voltage envelop and the students can see that one chip is there that it is used for the power factor activation technique is UC 3854 or 5 x. So 385x it can be 54, 55. So that is used for the this PFC technique.

The most common one is a single phase system based on the diode rectifier with a boost converter at the DC link side. It will be shown into, this is the figure you know. And this is the three phase version of it. So there is a challenge involving this three phase version of the boost converter. And we can, getting a current envelope is little bit challenging.

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AC to DC Converters (cont...)

- The main advantages of Fig.3 (a) topology are the improved line current quality and power factor of the system based on the active circuit in the DC link system.
- Similar concept has been utilized in a three-phase diode or controlled rectifier as shown in Fig.3 (b).
- A main advantage of the converter topology in Fig.3 (b) is the ability to control the DC link current and voltage under different load profiles.
- In this three-phase system, each diode conducts for 120 degrees, thus the line current can be a square wave with or without modulated waveform to improve line current harmonics.

The main advantage of the figure 3 a topology are the improved line current quality and power factor of the system based on the active circuit in the DC link system. Similar concept has been utilized in the three phase diode or the control rectifier as shown in the failure. The main advantage of the converter topology 3 b is the ability to control the DC link current and voltage under different load profile.

This is a three phase system, each diode conducts 120 degree. Thus line current can be square wave without any modulated waveform and to improve the line current harmonics. So this is for the three phase but in three phase since it is difficult to generate envelope, we require to but this kind of technique may not work fine and ultimately we have to sit down with the full control rectifier to get the power bidirectional wave.

And you know actually mostly we may require to put little bit of filters here to eliminate also this frequencies.

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Pulse Width Modulated (PWM) Voltage Source Converters (VSC)

Bridge-Connected PWM Rectifier

- Fig. 4(a) shows the fully controlled single-phase PWM rectifier in bridge connection, which uses four controlled power switches with antiparallel diodes to produce a controlled dc voltage V_0 .
- For appropriate operation of this rectifier, the output voltage must be greater than the input voltage, at any time ($V_0 > \hat{V}_s$).

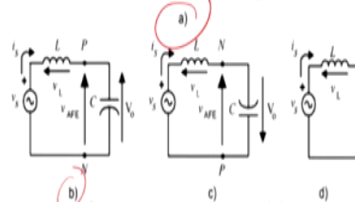
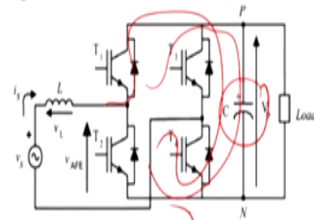


Fig. 4. Single-phase PWM rectifier in bridge connection. (a) Power circuit. Equivalent circuit with (b) T_1 and T_4 ON, (c) T_2 and T_3 ON, (d) T_1 and T_3 or T_2 and T_4 ON.

And apart from that there are few limitation to it because power handling capabilities since it is one bad rectifier and power handling capability will be very high and here different kind of topology is adopted. We can have a interleaved boost converter. So that is also possible so that it enhances the power quality in terms of the conduction because if you have a multiple switches we have shifted by some amount of load.

So ultimately current here does not become discontinuous and thus you get a better quality and correction become easier. Now let us come to the pulse width modulated PWM voltage source convert. Now let us take the full bridge converter. This is the figure a shows the full bridge fully controlled, single phase PWM rectifier which uses full control power switches with the antiparallel diode.

So current can be bidirectional while voltage blocking capability is unidirectional and with antiparallel diode to produce the control voltage in the DC link. What happen the power will be rectified here and you get a control voltage depending on its duty cycle. For the appropriate operation of this rectifier output voltage here you only get the boost topology, must be greater than the input voltage at any time.

So this output voltage V_0 require to be greater than V_s . That is one of the challenge here. So you are required to maintain this voltage higher. So what happen here once this is the b part of it. When this P 1 and this is the path essentially. When T_1 and T_4 are on, so ultimately this leads to the this part of the circuit and other is when T_2 and T_3 are on.

So ultimately you have this part of the circuit and when you have a short through stage or you have a short stage that is $T_1 T_2$, $T_1 T_3$ or $T_2 T_4$ are on. That means you short the capacitor. So these are the different mode of operation and you can boost the voltage in that way and ultimately what happen current cannot change unidirectionally. So once it is

flowing, then current will continue to flow through the diode once switch is off.

Then it will change. So this is the mode of operation. So if T 1 and T 4 are on this is let us say is mode 1 ON state, while T 3 T 4 are OFF state.

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Bridge-Connected PWM Rectifier (cont...)

➤ The possible combinations of switch operations in the converter are as follows:

❖ Switch T_1 and T_4 are in ON state while T_2 and T_3 are in OFF state, then

$$v_{AFE} = V_0 \text{ [Fig. 4(b)].}$$

❖ Switch T_1 and T_4 are in OFF state while T_2 and T_3 are in ON state, then

$$v_{AFE} = -V_0 \text{ [Fig. 4(c)].}$$

❖ Switch T_1 and T_3 are in ON state while T_2 and T_4 are in OFF state, or T_1 & T_3 are in OFF state while T_2 & T_4 are in ON state, then $v_{AFE} = 0$, [Fig. 4(d)].

➤ The inductor voltage can be expressed as:

$$v_L = L \frac{di_s}{dt} = v_s(t) - kV_0 \quad (1)$$

➤ Where, $k = 1, -1, \text{ or } 0$.

Then the voltage of this rectifier will be V_0 . Then we switch it over T 1 and T 4 are OFF state while T 2 T 3 are ON state then you get minus of the output voltage. If switches T 1 and T 3 are ON state while T 2 and T 4 are OFF state or T 1 or T 4 are in OFF state while T 2 and T 4 are in the ON state then this will be 0. The inductor voltage can be expressed as $V_L = L \frac{di_s}{dt} = v_s - kV_0$ and where you have k equal to either 1 or -1 or 0. This is the equations. So if k equal to one, then inductor voltage will be negative.

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Bridge-Connected PWM Rectifier (cont...)

➤ If $k=1$, then the inductor voltage will be negative, so the input current i_s will decrease its value.

➤ If $k=-1$, then the inductor voltage will be positive, so the input current i_s will increase its value.

➤ Finally, if $k=0$ the input current increase or decrease its value depending on v_s . This allows for a complete control of the input current.

So the input current i_s decreases its value and when it is -1, then inductor voltage will be positive. So the input current i_s will increase its value. And if $k = 0$ then the output current increases or decreases its value depending on the sign of v_s . That is depend on whether it is a positive cycle or negative cycle and allows to complete the control the input current.

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Three-phase PWM Voltage Source Converter

- It is well known that voltage-source inverters (VSIs), can reverse the power flow from the load to the dc link, that means, as a voltage source rectifier (VSR).
- However, a stand-alone VSR requires a special dc bus able to keep a voltage V_0 without the requirement of a voltage supply and this can be accomplished with a dc capacitor and a feedback control loop.
- The basic operation principle of VSR consists on keeping the load dc-link voltage at a desired reference value, using a feedback control loop as shown in Fig. 5

So now let us talk about, we have talked about the single phase converter. Now let us talk about the three phase speed of the voltage source converter. It is well known that the voltage source converter VSI can reverse power flow from the load to the DC link. That means, as the voltage source rectifier VSR. However, a standalone VSR require a special DC bus able to keep a voltage V_0 without requirement of the voltage supply.

And this can be accomplished with a DC capacitor and a feedback loop control, we will see it in the next slide. The basic operations of principle of the VSR consists of keeping the load DC link voltage at a desired level value using the feedback control as seen in this loop.

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Three-phase Voltage Source Converter (cont...)

- This reference value V_{0ref} , has to be high enough to keep the diodes of the converter blocked.
- Once this condition is satisfied, the dc-link voltage is measured and compared with the V_{0ref} .
- The error signal generated from this comparison is used to switch ON and OFF the valves of the VSC.

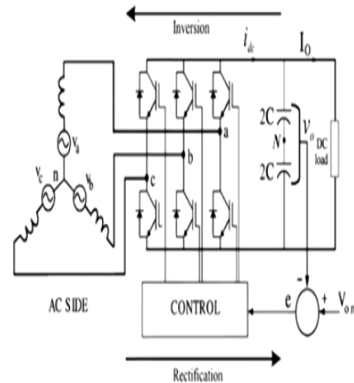


Fig.5 Operation principle of the VSC

You can see that you have a control since you are boosting. So you have a V output ref and what is actually you will sense it and subtract it and it will be put to the generally PI controller. From PI controller you will generate the reference for the switches and that will maintain that desired DC link voltage. So the reference value V output ref has to be high enough to keep that in a converter blocking state.

That is something you require to ensure. Once this condition is satisfied the DC link voltage is measured and compared with this V o ref. The error signal generated from the comparison is used to the switch ON and OFF value of the voltage source converter.

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Three-phase Voltage Source Converter (cont...)

- When the dc load current is positive (rectifier operation), the capacitor is being discharged, and the error signal becomes positive.
- Under this condition, the Control Block takes power from the supply by generating the appropriate PWM signals for the six power transistor switches of the VSR.
- In this way, current flows from the ac to the dc side, and the capacitor voltage is recovered.
- Inversely, when the dc load current becomes negative (inverter operation), the capacitor is overcharged, and the error signal asks the control to discharge the capacitor returning power to the ac mains.

When DC load current is positive, that means in a rectifier operation you are taking power from the AC side, the capacitor is being discharged and the error signal become positive. Under this condition the control block diagram takes power from the supply by

generating appropriate PWM signal for the six power transistor switches up the VSR. In this way current flow from the AC to the DC side and the capacitor voltage is recovered.

And inversely when power required to deliver to the grid, then the DC load current becomes negative. That is inverter operation. The capacitor is overcharged and the error signal has the control to discharge the capacitor returning power to the main grid.

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Multilevel Converters

- Multilevel converters are power-conversion systems composed by an array of:
 - ❖ power semiconductors and
 - ❖ capacitive voltage sources that when properly connected and controlled, can generate a multiple-step voltage waveform with variable and controllable frequency, phase, and amplitude.
- The stepped waveform is synthesized by selecting different voltage levels generated by the proper connection of the load to the different capacitive voltage sources.
- This connection is performed by the proper switching of the power semiconductors.

Now we will talk about the multilevel converter because there are two reasons of choosing a multilevel converter. One is that problem of the THD. Since the inverter generates square waves or quasi square wave for this two level inverter if you go to the multilevel inverter then it generates the staircase waveform. Closer to the staircase, more will be the stairs, more will be more close to the sine wave and moreover waiting on the switches can be reduced.

Considering that multilevel converters are power conversion system composed by area of power electronics semiconductors and capacitor voltage sources that when properly connected and controlled it can generate a multiple step voltage waveform with variable and the controllable frequency phase and amplitude.

The stepped waveform is synthesized by selecting different voltage levels generated by the proper connections of the load to the different capacity voltage sources. The connection is performed by proper switching of the power semiconductors.

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Multilevel Converters (cont...)

- Multilevel converters are currently considered as one of the industrial solutions for high dynamic performance and power-quality demanding applications, covering a power range from 1 to 30 MW.
- Some of the significant advantages of multilevel converters are:
 - ❖ Higher voltage operating capability ✓
 - ❖ Lower common-mode voltages
 - ❖ Reduced voltage derivatives dv/dt
 - ❖ Voltages with reduced harmonic contents, near sinusoidal currents, smaller input and output filters (if necessary)
 - ❖ Increased efficiency, and, in some cases, possible fault-tolerant operation

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Voltages with reduced harmonic content, near sinusoidal currents, smaller input and output filters if necessary, increased efficiency and in some cases possible the fault-tolerant operation.

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Multilevel Converters (cont...)

- The number of levels of a converter can be defined as the number of steps that can be generated by the converter between the output terminal and any arbitrary internal reference node within the converter.
- It is a dc-link node denoted by N and called neutral.
- To be called a multilevel converter, each phase of the converter has to generate at least three different voltage levels.
- Fig.6 shows some single phase examples of multilevel concepts and their respective waveform.

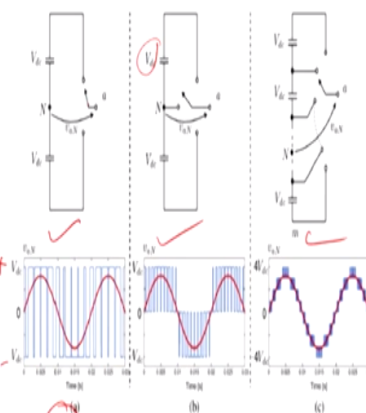


Fig.6) Converter output voltage waveform:
a) two level, b) three level, c) nine level.

So you can have multiple switches. You can connect this point, this pole at positive V_{dc} or negative V_{dc} and thus voltage can switch over to $+V_{dc}$ to $-V_{dc}$. This is your two level or you may have the intermediate level and in V_{dc} you can connect to the midpoint

of the V dc capacitor which is assumed to be zero and also the negative V dc. So you have three level inverter.

Same way, you can have this thing multilevel staircase inverter and it is close to the sine wave. The number of levels of the converter can be defined as the number of steps that can be generated by the converter between the output terminal and any arbitrary terminal reference node with the converter. It is the DC link node denoted by N and called neutral.

To be called a multilevel converter, each phase of the converter has to generate at least three different voltage level. So this figure shows that some single phase example of the single phase example of the multilevel converter and respective waveform. This is for the two level, this is for the three level, and this is for the multilevel and this is for nine level let us say because you have you can see there are nine levels.

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Multilevel Converter Topologies

- Multilevel converters can be classified into two major groups based on independent dc source and their structure as illustrated in Fig.7.

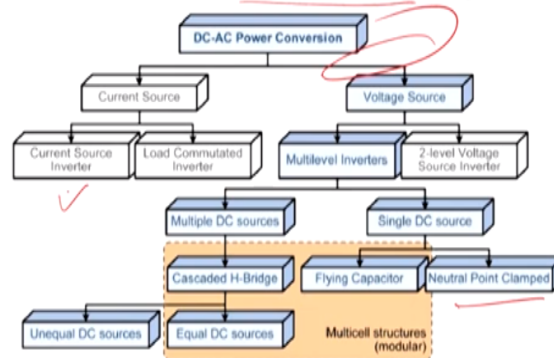


Fig.7: Multilevel converter classification

So we can classify the multilevel converter topologies. Multilevel converter topology can be classified into two major group based on dependent DC sources and structures as illustrated in figure 7. So DC to AC power conversion, generally we go for this voltage source. So we may have a voltage source that is multilevel inverters and two level inverter considering the harmonic content and the device gating, multilevel converter is been preferred.

And multilevel converter can be broadly classified into multiple DC source and the single DC resource. And in the single DC source you will have flying capacitor and you have a neutral point clamped capacitors. And here multilevel DC source thereafter cascaded H-bridge that are equal DC source and unequal DC source. Same way you may have a current source that can be splitted to the current source inverter and load commutated inverter.

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Multilevel Converter Topologies (cont...)

- The most known and established multilevel topologies are:
 - ❖ The neutral point clamped (NPC) or diode clamped,
 - ❖ The flying capacitor (FC) or capacitor clamped, and
 - ❖ The cascaded H-bridge (CHB).

A) Neutral Point Clamped Converters

- An NPC converter is composed of two two-level VSCs stacked one over the other with some minor modifications (see Fig.8).

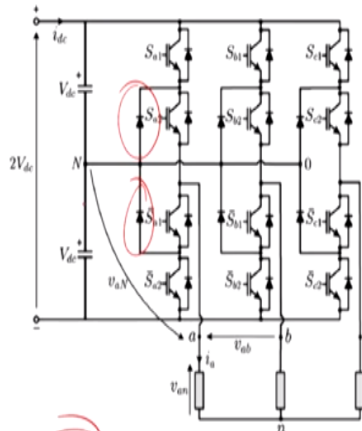


Fig.8: Three-level neutral point clamped power circuit

So this is the one of the diode clamped inverter topology, multi-converter topology. It is the best known and established multilevel topologies are the neutral point clamp NPC or the diode clamped. The flying capacitor FC or capacity clamped. The cascade H-bridge or CHB. The neutral point clamped converter. An NPC converter is composed of two level VSCs stacked one over the other with some minor modification.

We can see that this is the three level neutral clamped circuits. So this is the conducting diode. One of the disadvantage of this topology is that the number of diode is highly increased when level increases more than four.

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Neutral Point Clamped Converters (cont...)

- Note that there are only two control signals per phase; the other two switches receive inverted gating signals to avoid the dc-link short-circuit.
- Fig.9 shows the three different switching states for one phase of the NPC and their corresponding output voltage levels.
- The obtained equivalent circuit is highlighted to show how the output node a is linked to the positive, neutral, and negative nodes of the dc side circuit

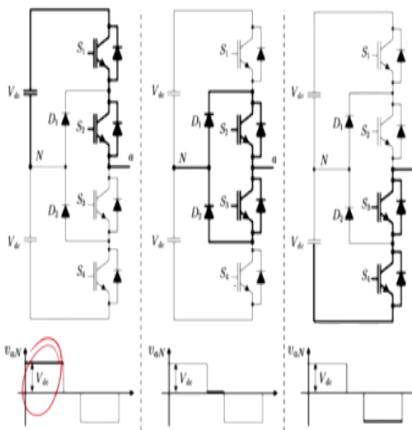


Fig.9: 3-level NPC switching states & corresponding output voltage levels.

So this is a neutral point clamped converters. So ultimately once you require to generate the plus V dc you will have this and if you want to generate the minus V dc then S 3 S 4

are closed. And once you wanted to generate the voltage zero, then both S 3 S 4 are switched on and depending on the polarity of the depending on this whether this voltage is more than these or reverse the conducting diode will conduct.

So note that there are only two signals per phases. The other two switches receive inverted gating signal to avoid the DC link short circuit. Figure 9 shows the three different switching states for one phase of the NPC and the corresponding output voltage levels. The obtained equivalent circuit is highlighted to show how the output node a is linked to the positive, neutral and the negative node of the DC circuits.

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Flying Capacitor (FC) Converters

- The FC topology is somewhat similar to the NPC, with the main difference being that the clamping diodes are replaced by flying capacitors, as shown in Fig. 10.
- The zero level is obtained by connecting the load to the positive or negative bar through the flying capacitor with opposite polarity respect to the dc-link.
- Only two gating signals are necessary per phase to avoid dc-link and flying capacitor short-circuit.
- The inverted gating signals are related to different switching devices, as shown in Fig. 10.

Fig.10: Three-level flying capacitor power ckt 10.

Now flying capacitor. The FC topology is somewhat similar to the NPC so there is a flying capacitor and number of flying capacitor is almost half of the conducting diode. So this is the one of the advantage that number of capacitor is less. With the main difference being that the clamping diode is replaced by the flying capacitor but with reduced number.

The zero level is obtained connecting the load to the positive or the negative bar to the flying capacitor with positive polarity respect to the DC link. Only two gating signals are necessary per phase to avoid the DC link and the flying capacitor being short circuited. The inverted gating signals are related to the different switching devices as shown in the figure 10. So this is the flying capacitor converter. And we can see how it is conducting if you wish to generate this voltage.

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Flying Capacitor (FC) Converters (cont...)

- The switching states and their equivalent power circuits with the corresponding output voltage levels are illustrated in Fig. 11.
- The FC topology has a modular structure and can be more easily extended to achieve more voltage levels and higher power rates.



Fig.11: Three-level FC switching states and corresponding output voltage levels

So it is same but when you generally try to generate negative voltage generally the S 1 and S 3 require to be turned on where in that case S 2 and S 3 require to be turned on. And here S 3 and S 4 require to be turned on, that is same, is same as that of this diode clamped inverter. So this is the changes while zero can be done through if you are going essentially how you are going that is also essential to reduce the switching losses and stage transition occur with the minimum switching state.

If you are in a S 1 S 2 then definitely you will switch it on S 1 and S 3 to get the zero voltage. If you are in S 3 S 4 and to get the zero voltage, you should switch off switch on S 4 and S 2. That also give you the zero voltage. So you can accomplish different stage of the voltage by zero voltage switching, by one change of state.

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Cascaded H-Bridge (CHB) Converters

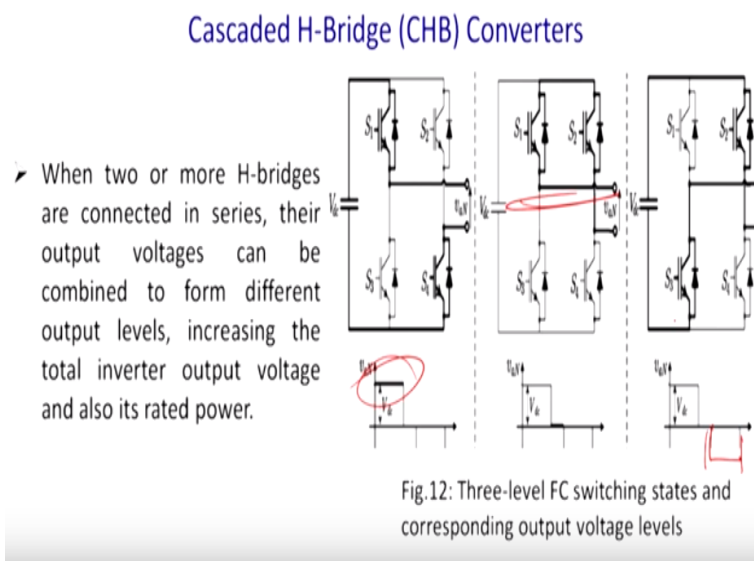
- CHBs are multilevel converters formed by the series connection of two or more single-phase H-bridge inverters.
- Each H-bridge corresponds to two voltage source phase legs, where the line-line voltage is the converter output.
- A single H-bridge converter is able to generate three different voltage levels. Each leg has only two possible switching states, to avoid dc-link capacitor short-circuit.
- The zero level can be generated connecting the phase outputs to the positive or the negative bars of the inverter (only the first one is illustrated in Fig. 12).

So we can have also another important topology is cascaded H-bridge and are multilevel

converter formed by the series connections of the two or the single phase H-bridge converter. The each H-bridge corresponds to two voltage source phase legs with phase legs and where the line voltage is the converter output. A single H-bridge converter is able to generate three different voltage level.

Each leg has only two possible switching state to avoid the DC link capacitor to the short circuit. And one of the disadvantage of the cascaded multilevel inverter that it require isolated DC sources. But, it has a modularity in nature and you can put them in cascade manner and you can build any of the level you wanted. The zero level can be generated connecting the phase output to the positive or the negative bars of the inverter. Only the first one is illustrated here.

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So see that this is how you can generate the one of the you can cascade it to the many level. Once this S 1 and S 4 is closed you get a positive DC voltage and once you decided to short this upper leg since this was conducting, so you get a zero voltage. Similarly if you switch it off this and also this and this is on then you get supposed to get the minus V dc. So this is the way you are going to get the different voltage and you can cascade them so you can get the staircase waveform.

Thank you for your attention. I am looking forward to your next courses. We will continue with the application of the power electronics in the microgrid. Thank you.