ECE 404-TD / 504-TD

ST: T&D APPLICATIONS OF VOLTAGE SOURCE CONVERTERS

SESSION no. 20
1. For a four-level NPC converter, find all the available switching states. Let the total dc link voltage be 8.0kV.
   a. List the switching states in a table showing the voltage across each switch and the components of a space vector representation thereof. You may work in a per unit system of your choice if you prefer.
   b. Create a plot similar to what was presented in class. Plot all the vectors. Label each vector in the first hexant; that’s plenty. You can check your plot using Prof. Corzine’s reference.

2. Find and plot one cycle of the dc current that accompanies a three-level space vector PWM that yields a vector of $0.60 \, V_{dc} / 40^\circ$ Volts. The load current is 200 Amps with a power factor of 1.00. A number for $V_{dc}$ is not necessary, but if you want one, make one up and declare it.

3. For a four-level NPC, apply sine-triangle modulation at a 5kHz:50Hz frequency ratio between triangle and sine wave frequencies. Set the sine wave’s amplitude at $\frac{2}{3}$ of the sum of the applied triangle wave. Let the dc link voltage be 8kV.
   a. Plot the triangle waves superimposed on a three phase sine wave.
   b. Show one (sine) cycle of the resulting pulse width modulation.
   c. Show a harmonic spectrum that reveals at least the first half dozen nonzero voltage harmonics.

4. For a Multimodal Multilevel Converter (MMC) with four-modules in each leg and balanced capacitor voltages of 2kV for each switch and diode,

   a. Determine the voltage stair step waveform with the same switching losses as the NPC converter of problem 3. Use a fundamental output frequency of 50 Hertz.
   b. Identify the fundamental and lowest nonzero harmonic output line-to-neutral voltage, magnitude and frequency. Assume the inductors have no voltage drop.
   c. For a machine load that is modeled as a 50 Hz voltage source of the same amplitude as the fundamental component of the terminal voltage, but lagging three degrees, behind a reactance of 0.35 Ohms at 50 Hz, find the fundamental current and the lowest nonzero current harmonic, magnitude and frequency.
\( s = \frac{\omega_s - \omega_m}{\omega_s} \)
ECE 404 / 504

T & D Applications of Voltage Sourced Converters

Lesson 20

NO CLASS Lesson 24; Exam compensatory time

Induction Machine...

2 complete three phase sets of windings give us 4 poles

Squirrel cage
Wound rotor

Advantages

- Ruggedness
- Variable speed
- Maintenance
- Efficiency
- Low speed performance
- Size and weight
- Protection

Specific advantages:
• A stable, useful performance AS A GENERATOR with a slight overspeed
• Ability to use both stator and rotor as higher bandwidth ports for control, energy I/O, and protection.
Induction Motor Example

\[ R_1 := 0.02 \quad R_2 := 0.025 \quad \text{lagging} := 1 \]

\[ X_1 := 0.06 \quad X_2 := 0.04 \quad X_m := 3.5 \]

\[ V_1 := 1.00 \quad \omega_s := 1.00 \]

Find current input.

\[ s := 0.025 \]

\[ \frac{V_m - V_1}{R_1 + j \cdot X_1} + \frac{V_m}{j \cdot X_m} + \frac{V_m}{\frac{R_2}{s} + j \cdot X_2} = 0 \]

This \( V_m \) is the air gap voltage.

\[ V_m := \frac{\left( \frac{V_1}{R_1 + j \cdot X_1} \right)}{\frac{1}{R_1 + j \cdot X_1} + \frac{1}{j \cdot X_m} + \frac{R_2}{s} + j \cdot X_2} = 0.964 - 0.051i \]
Input Current is

\[ I_1 := \frac{V_1 - V_m}{R_1 + j \cdot X_1} = 0.951 - 0.288i \quad |I_1| = 0.994 \]

\[ \arg(I_1) = -16.852 \cdot \text{deg} \]

Find torque.

\[ I_2 := \frac{V_m}{\frac{R_2}{s} + j \cdot X_2} = 0.96 - 0.09i \]

\[ \text{torque} := \frac{(|I_2|)^2 \cdot R_2}{s \cdot \omega_s} = 0.93 \]

Power in, power out, and efficiency.

\[ P_{\text{in}} := \text{Re}(V_1 \cdot I_1) = 0.951 \]

\[ P_{\text{out}} := (|I_2|)^2 \cdot R_2 \cdot \frac{(1 - s)}{s} = 0.907 \]

\[ \eta := \frac{P_{\text{out}}}{P_{\text{in}}} = 95.3 \cdot \% \]
Power Factor

\[ pf := \frac{P_{\text{in}}}{|V_1| \cdot |I_1|} = 0.957 \cdot \text{lagging} \]

Now let's generalize the equations over a range of slip or rotor speed.

\[ V_m(\text{slip}) := \frac{\left( \frac{V_1}{R_1 + j \cdot X_1} \right)}{\frac{1}{R_1 + j \cdot X_1} + \frac{1}{j \cdot X_m} + \frac{1}{\frac{R_2}{\text{slip}} + j \cdot X_2}} \]

\[ I_m(\text{slip}) := \frac{V_1 - V_m(\text{slip})}{R_1 + j \cdot X_1} \]

\[ \omega(\text{slip}) := \omega_s \cdot (1 - \text{slip}) \quad \text{Rotor Speed} \]
Find current input for a range of slip...

\[ |I_1(\text{slip})| \]

...and rotor speed

\[ |I_1(\text{slip})| \]
torque

\[ I_{2m}(\text{slip}) := \frac{V_m(\text{slip})}{R_2} + j \cdot X_2 \frac{\text{slip}}{} \]

torque(\text{slip}) := \left( \frac{|I_2(\text{slip})|^2}{R_2} \right) \frac{\text{slip} \cdot \omega_s}{\text{slip} \cdot \omega_s} \]

![Graph showing the relationship between torque and slip, with labels for Motor, Generator, and Braking phases.](image)
Power in, power out, and efficiency

\[ P_{\text{in}}(\text{slip}) := \text{Re} \left( V_1 \cdot I_1(\text{slip}) \right) \]

\[ P_{\text{out}}(\text{slip}) := \left( |I_2(\text{slip})| \right)^2 \cdot R_2 \cdot \frac{(1 - \text{slip})}{\text{slip}} \]

\[ \eta(\text{slip}) := \begin{cases} 
\frac{P_{\text{out}}(\text{slip})}{P_{\text{in}}(\text{slip})} & \text{if } \text{slip} > 0 \\
\frac{P_{\text{in}}(\text{slip})}{P_{\text{out}}(\text{slip})} & \text{if } \text{slip} < 0 
\end{cases} \]
Power factor

$$\text{pf}_{\text{lin}}(\text{slip}) := \frac{|P_{\text{in}}(\text{slip})|}{|V_1| \cdot |I_1(\text{slip})|}$$