Exam 1

Name: ______________________________

The exam is taken remotely. Any material is allowed.

1.1 Direct MPC of a Medium Voltage Drive System

Consider the three-phase inverter drive system shown in Fig. 1. A three-level neutral point clamped (NPC) converter with the total dc-link voltage V_{dc} is connected to a squirrel-cage induction machine. The neutral point potential is assumed to be zero. The rated machine values are provided in Table 1. The system parameters are summarized in Table 2.

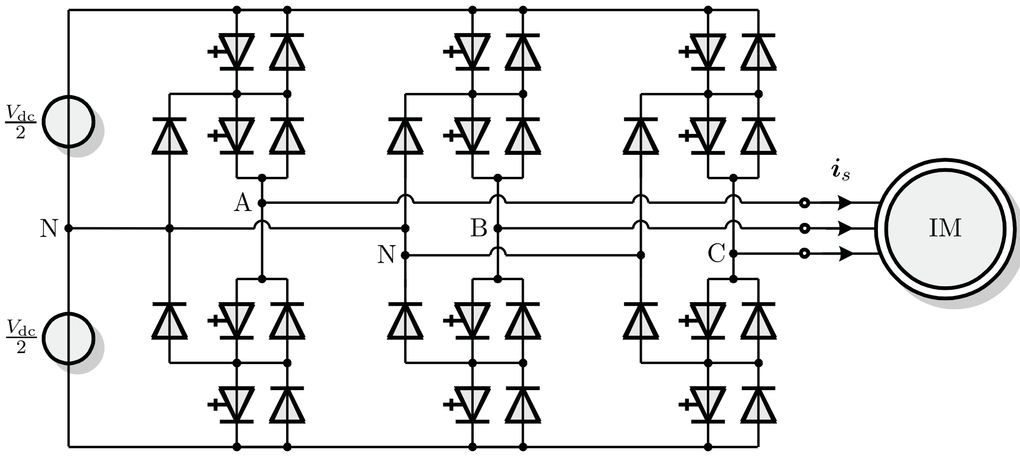

Figure 1: Three-level three-phase neutral point clamped inverter driving an induction machine with a fixed neutral point potential

Parameter	Symbol	SI value
Voltage	V_R	3300 V
Current	I_R	356 A
Apparent power	S_R	2.035 MVA
Angular stator frequency	ω_{sR}	$2\pi 50$ rad/s

Table 1: Rated values of the induction machine

1. Compute the per unit values of the stator and rotor resistances, R_s and R_r, respectively, stator and rotor leakage reactances, X_{ls} and X_{lr}, respectively, mutual reactance X_m, and dc-link voltage V_{dc}. (2 points)
2. Assume direct MPC. The state variables are the stator current and rotor flux in the $\alpha\beta$-plane, i.e., $\boldsymbol{i}_{s,\alpha\beta}$ and $\boldsymbol{\psi}_{r,\alpha\beta}$, respectively, and output variable the stator current $\boldsymbol{i}_{s,\alpha\beta}$. Define the control input $\boldsymbol{u}$. (1 point)

Parameter	Symbol	SI value
Stator resistance	R_s	$57.61\,\mathrm{m\Omega}$
Rotor resistance	R_r	$48.89\,\mathrm{m\Omega}$
Stator leakage inductance	L_{ls}	$2.544\,\mathrm{mH}$
Rotor leakage inductance	L_{lr}	$1.881\,\mathrm{mH}$
Main inductance	L_m	$40.01\,\mathrm{mH}$
Number of pole pairs	p	5
Dc-link voltage	V_{dc}	$5.2\,\mathrm{kV}$

Table 2: Drive parameters in the SI of the three-level NPC inverter drive system

3. The *main* control objective of the controller for the *medium voltage* (MV) drive system is to regulate the stator current $\boldsymbol{i}_{s,\alpha\beta}$ along its reference $\boldsymbol{i}_{s,\mathrm{ref},\alpha\beta}$. State a proper objective function J given a prediction horizon of N_p time steps. (1 point)

4. Given that a switch transition in a phase leg from 1 to -1, and vice versa, is only possible via an intermediate zero switch position, i.e., a switching constraint is implemented, formulate the optimization problem underlying MPC. How can the optimization problem be solved? (2 points)

5. Would you rather use the ℓ_1-norm or the ℓ_2-norm in the objective function J for the tracking error term? Which norm would you use for the control effort term (i.e., the penalty on the switching)? (2 points)

6. For $N_p = 1$, how many are the candidate solutions for the above MPC problem in the worst-case scenario? What would that scenario be? (2 points)

7. For $N_p = 5$, derive the matrices $\boldsymbol{\Gamma}$, and $\mathbf{Y}$ as a function of the discrete-time state-space matrices $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$. Moreover, derive the matrices $\boldsymbol{S}$, and $\boldsymbol{E}$. State the equivalent integer least-squares (ILS) problem. How can this ILS be solved efficiently? What is the dimension of the optimization variable $\boldsymbol{U}$? (5 points)

8. Assume that the neutral point potential v_n of the inverter in Fig. 1 is floating (i.e., $v_n \neq 0$). In such a case, it should be controlled. State the new state and output vectors of the system. (2 points)

9. Describe how matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ of the new system are different compared to those of the system where a zero neutral point potential was assumed. (2 points)

10. State the new objective function J. Assume the reference value of the neutral point potential to be $v_{n,\mathrm{ref}}$. Consider the switching constraint and formulate the optimization problem underlying MPC. How can the optimization problem be solved? (2 points)

1.2 Model Predictive Pulse Pattern Control (MP^{3}C)

Consider a three-level NPC inverter driving an induction machine. Assume that MP^{3}C is employed to control the drive system.

1. What is the “optimal” stator flux reference trajectory? Does it change when changing the torque reference? Does it change when changing the speed reference? (3 points)

2. What does MP^{3}C control and what does it manipulate? (1 point)

3. Consider one phase, a positive switching transition and too large a stator flux, i.e., the flux error is negative. What action will the controller take? (2 points)

4. Consider that the dc-link of the converter is connected via a rectifier to a *single-phase* railway grid with the fundamental frequency $16\frac{2}{3}$ Hz, i.e., a voltage harmonic appears on the dc-link at $33\frac{1}{3}$ Hz. Assume that the fundamental frequency of the machine is $f_1 = 50$ Hz. What is the impact of the aforementioned voltage harmonic on the spectrum of the stator voltage, assuming that OPPs are applied in open loop? (6 points)

1.3 Indirect MPC of a Grid-Connected NPC Inverter with an LCL Filter

Consider a three-level NPC with fixed neutral point potential connected to the grid with voltage $\boldsymbol{v}_g$ via an intermediate LCL filter, see Fig. 2. The grid reactance and resistance are X_g and R_g, respectively. The converter-side filter reactance X_{lc}, grid-side filter reactance X_{lg}, and capacitance X_c have internal resistors R_{lc}, R_{lg}, and R_c, respectively.

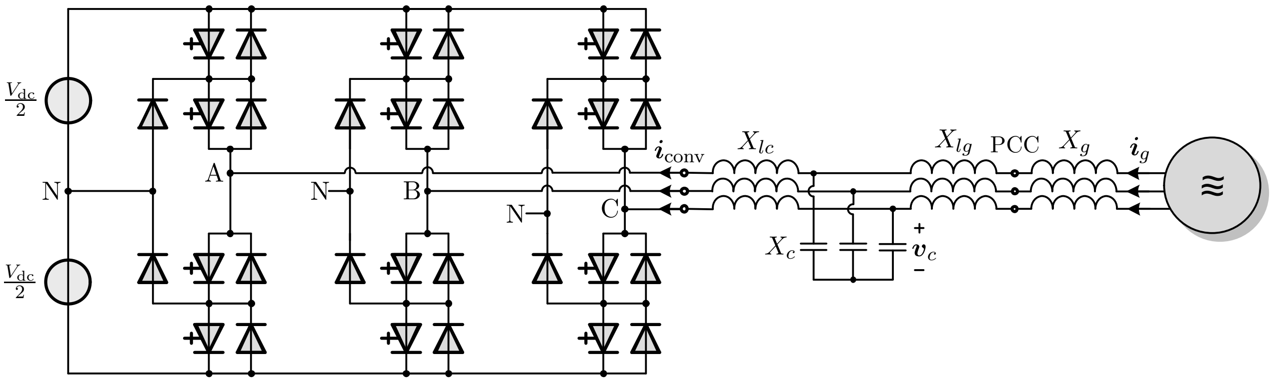

Figure 2: Three-level three-phase neutral point clamped inverter connected to the grid via an intermediate LCL filter. The neutral point potential is fixed and the internal resistors of the passive components are not depicted.

1. Draw the harmonic model of the system in stationary ($\alpha\beta$) orthogonal coordinates. (1 point)

2. Assuming that a modulation stage with CB-PWM follows the MPC-based controller, define the state $\boldsymbol{x}$, input $\boldsymbol{u}$ and output $\boldsymbol{y}$ vectors. Assume (a) that the grid voltage is a state but not output variable, and (b) all the other state variables are also output variables. (2 points)

3. State the objective function J for the prediction horizon N_p and the constraints. Hint: Remember that the output of MPC is fed into a modulation (CB-PWM) stage. (2 points)

4. What type of constraints would you impose on the state/output variables? Justify your answer. (1 point)

5. Assume that you want to limit the output variables between some minimum and maximum values. Derive the inequality constraints as a function of the state vector. What is the new objective function J? (5 points)

6. Formulate the optimization problem. What is the dimension of the optimization variable as a function of the prediction horizon N_p? (2 points)

7. What are the inputs and the outputs of the formulated MPC scheme? (2 points)

8. How can the optimization problem be reformulated so that it can be solved efficiently using off-the-shelf solvers? (1 point)

9. What is the preferred option, to formulate the MPC problem in stationary ($\alpha\beta$) or in rotating (dq) coordinates? Justify your answer. (2 points)

1.4 General Questions

1. Assume that a direct MPC scheme with reference tracking needs to be designed. What are the basic required steps to this end? (2 points)

2. Is direct MPC with reference tracking a good choice for grid-connected converters? Justify your answer. (1 point)

3. Why are OPPs (with minimum I_{TDD}) difficult to control in closed-loop using a classic (linear) controller? (2 points)

4. What is the I_{TDD} of SHE compared to standard OPPs? (1 point)

5. Consider n-level OPPs, with $n = 2, 3, 5, \ldots$. What is the type of optimization problem that needs to be solved in order to compute the n-level OPPs? (2 points)

6. What is the difference between direct and indirect MPC schemes? (1 point)