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MIDDLE EAST TECHNICAL UNIVERSITY

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EE498 Control System Design and Simulation Term Project

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MPC of Permanent Magnet Synchronous Generator with 2 L-VSI Grid-Side and Passive Generator Side Converters of a Wind Turbine

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1 Introduction

This project focuses on Model Predictive Current Control Application for a surface mount permanent magnet synchronous machine wind turbine. The model used is the electrical model for the machine. Considering the complicated and highly nonlinear aerodynamic system of the wind turbines,the focus is chosen as the power converters. MPC is a relatively new application in power electronics yet a promising control method. The simplified model of the turbine is provided and the MPC code is generated in MATLAB and Simulink.

2 Mathematical Model

[1],[3], [7],[4], [5]

A Wind Turbine Model is seen in figure 1. The model power converter topology contains a diode rectifier for rectifying the AC voltage to DC first in order to change the frequency and magnitude of the generator side and integrate generator side 3 phase to grid side. DC link voltage is connected to a 2 level Voltage Source Inverter whose configuration can be seen in figure 2.

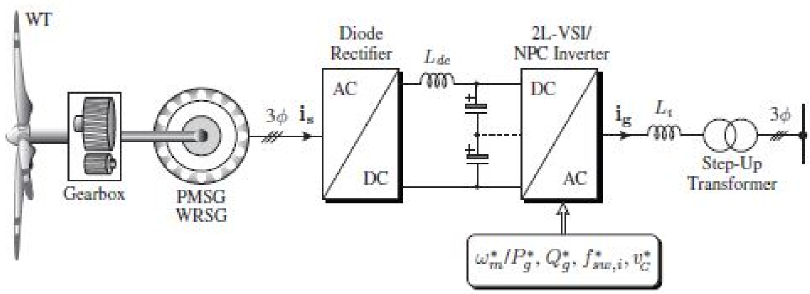

Figure 1: Passive Generator Side and 2LVSI Grid Side SPMG [8]

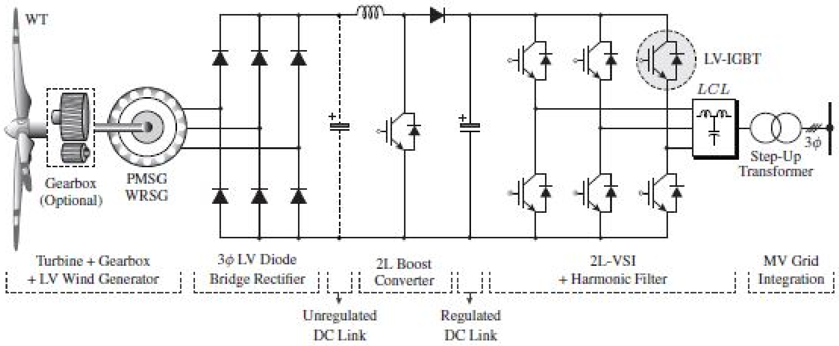

Figure 2: Detailed Circuit Configuration for Passive Generator Side and 2LVSI Grid Side SPMG [8]

For the models given above, the voltage of the grid side is determined by the switching sequence applied to the generator. From now on, in order to simplify the MPC computations dq frame will be used for currnent and voltage waveforms. For this abc to dq frame Park Transformation is used.

In order to understand this concept, let us consider the abc and dq frame illustration shown in figure 5.

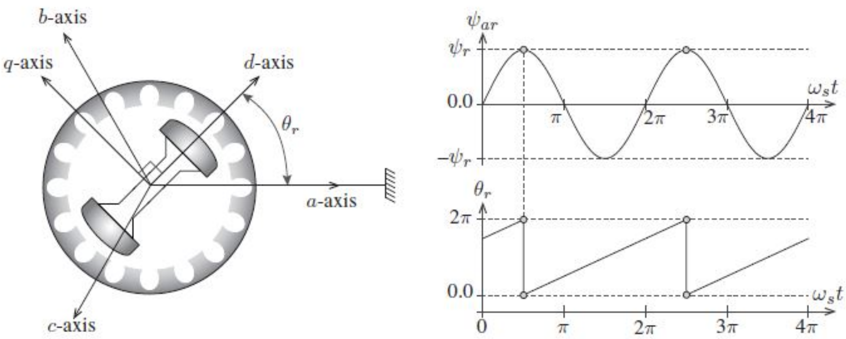

Figure 3: Representation of abcand dq frames of SPMG and angular correspondence[8]

Hence, the dq voltages will be the inputs of the mathematical model to be built, whereas the dq frame currents will be the state variables. The output to be observed can be selected anything. However, since the cost function is built in order to maximize the real power and minimize the reactive power, which are directly related with d and q axis currents respectively, the power is selected to be the output to be observed.

It is also important to note that the wind turbine can operate in 4 quadrants as seen in 4. Once again, for simplicity we will assume that the operation is in 2nd quadrant which is the generation mode.

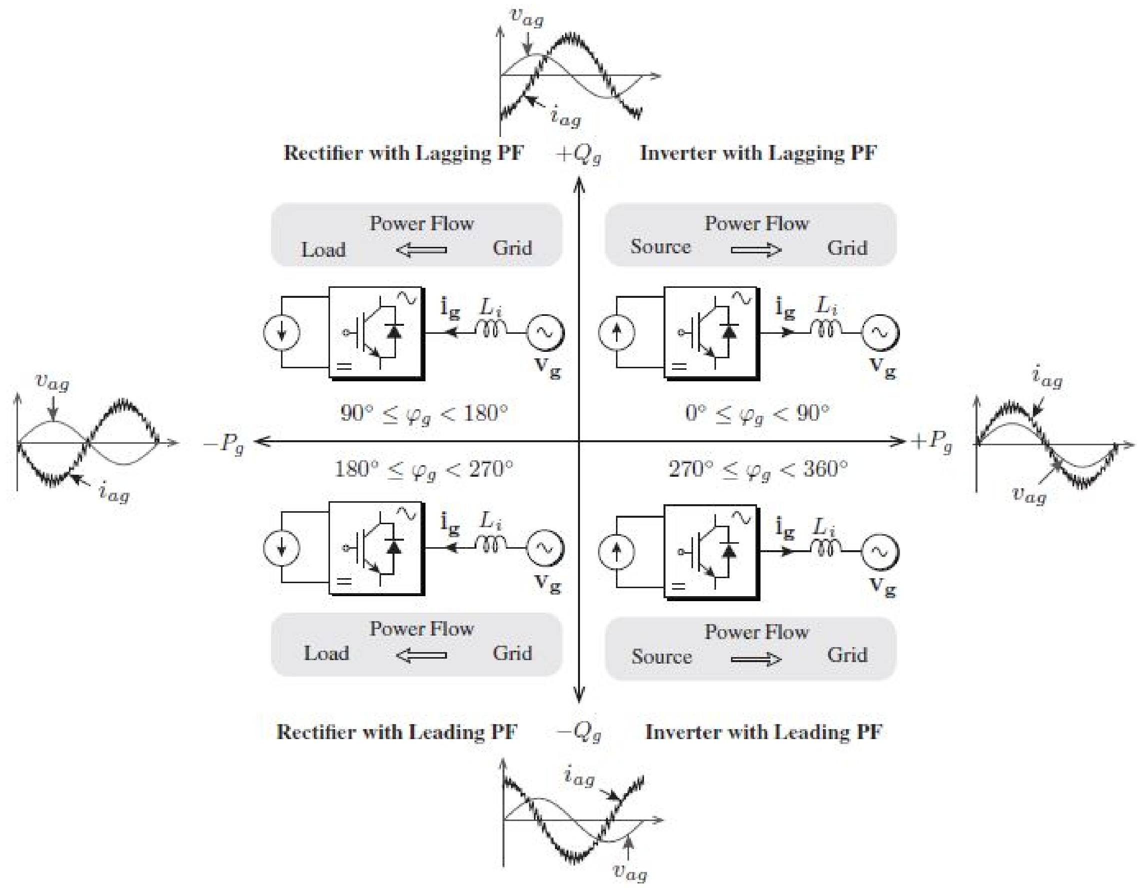

Figure 4: 4 Quadrant Operation for the Wind Turbine [8]

The continuous time model for the stator side (before the rectifier) is:

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_{ds}} & \frac{\omega_r L_{qs}}{L_{ds}} \\ -\frac{\omega_r L_{ds}}{L_{qs}} & -\frac{R_s}{L_{qs}} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ds}} & 0 \\ 0 & \frac{1}{L_{qs}} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_r \psi_r}{L_{qs}} \end{bmatrix}.$$

Figure 5: Stator Side Continuous Time Model [8]

For a surfacemount machine $L_d s$and $L_q s$ are the same. A similar model for the grid side 3 phase is accurate. As seen, the model depends on the rotor speed, which for simplicity, will be assumed as constant.

Similarly, the grid side discrete time current representation is shown in **??**

$$\begin{bmatrix} i_{dg}(k+1) \\ i_{qg}(k+1) \end{bmatrix} = \mathbf{\Phi} \begin{bmatrix} i_{dg}(k) \\ i_{qg}(k) \end{bmatrix} + \mathbf{\Gamma_i} \begin{bmatrix} v_{di}(k) \\ v_{qi}(k) \end{bmatrix} + \mathbf{\Gamma_g} \begin{bmatrix} v_{dg}(k) \\ v_{qg}(k) \end{bmatrix}.$$

$$\begin{bmatrix} v_{di}(k) \\ v_{qi}(k) \end{bmatrix} = v_{C1}(k) \underbrace{\begin{bmatrix} \cos\theta_g(k) & \sin\theta_g(k) \\ -\sin\theta_g(k) & \cos\theta_g(k) \end{bmatrix}}_{\mathbf{T}_{\alpha\beta/dq}} \begin{bmatrix} \mathbf{T}_{abc/\alpha\beta} \end{bmatrix} \begin{bmatrix} s_{ai1}(k) \\ s_{bi1}(k) \\ s_{ci1}(k) \end{bmatrix}$$

Figure 6: Grid Side General Discrete Time Model [8]

In the above equation the subscript g represents the grid and i represents the inverter. As mentioned the inverter voltages are controlled with 8 space vector switches and these switch states with the rotational angle decide the dq voltages at a given time and they are the input of the above 6. Moreover, the grid side voltage is assumed to be a stable constant bus and will be assumed to be constant (and will be subtracted from the inverter side voltage $v_{d/qi}$ like a a reference frame). Following estimations 7 are used according to [8]

$$\mathbf{\Phi} \approx [\mathbf{I} + \mathbf{A}\,T_s] \approx \begin{bmatrix} 1 - \frac{r_t T_s}{L_t} & \omega_g T_s \\ -\omega_g T_s & 1 - \frac{r_t T_s}{L_t} \end{bmatrix}$$

$$\mathbf{\Gamma_i} \approx \mathbf{B_i}\,T_s \approx \begin{bmatrix} \frac{T_s}{L_t} & 0 \\ 0 & \frac{T_s}{L_t} \end{bmatrix}, \ \mathbf{\Gamma_g} \approx \mathbf{B_g}\,T_s \approx \begin{bmatrix} -\frac{T_s}{L_t} & 0 \\ 0 & -\frac{T_s}{L_t} \end{bmatrix}.$$

Figure 7: Grid Side General Discrete Time Model Matrices' Estimations [8]

- **Calculation of Reference Currents**
  dq axis reference currents will be obtained from the DC side.
- **Prediction of Future Behaviour of the Grid Currents**
  This behaviour will be obtained from Model Predictive Control
- **Cost Function**
  Regulation of the active power is dependent on the d-axis current, whereas the reactive power depends on q-axis current. Switching frequency minimisation will be eliminated for simplicity and cost function will be generated for maximising the real power output.

In the lectures, we have generated the linear quadratic regulation to decrease the states to 0 and formed the objective functions accordingly, hence the output converges to 0 as well. For a wind turbine system, however, it is important to note here that we have taken the grid current as our state variable whose d axis current is desired to have a nonzero value for keeping our power constant, which should have a nonzero constant value for all the time. Therefore, the cost function wants to minimise the difference between the reference grid currents and the actual grid currents. Therefore, converging to 0 will be accepted as converging to the reference value. This goal can be expressed as in equation 1.

$$G(k) = \lambda_{id}[(i_{dref}(k+1) - i_{dpredicted}(k+1))^2] + \lambda_{iq}[(iqref(k+1) - i_{qpredicted}(k+1))^2] \quad (1)$$

3 System Constraints and Parameters

There are a number of different wind turbine generator types with different power specifications. Using a passive generator side machine I have selected a low power machine for modelling and its parameters to be used are shown in the table1.

Table 1: Parameters of low-speed PMSG for passive generator-side converters

Parameter	**Rated Values**
P_s (Stator active power)	-740 kW
Q_s (Stator reactive power)	152 kVAR
V_s (Stator phase rms voltage)	398 V
I_s (Stator phase rms current)	632 A
$f_s - \omega_s$ (Generator electrical stator frequency)	9.75 Hz-61.25 rad/s

Therefore, while simulating there will be a constraint on the input voltages not to exceed the rated value provided. We are using 540 V DC voltage as the passive rectification output, thinking the operation ideal. When the switching signal sequence in MATLAB as a separate code is run, the voltages change within a range. That is:

$$-360 \leq v_{ds}, v_{qs} \leq 360 \tag{2}$$

which is already smaller than the rated value. In the MATLAB part we will see that the input does not exceed the given value above for the initial state $x_0 = [350350]^T$ being used.

Moreover, since we are interested in the grid side, the filtering resistance $R_i = 0.1\Omega$ and the filtering inductance $L_i = 0.16mH$ [2] will be used for the model derived in figures 7 and 1, 2.

4 MATLAB Model Predictive Control Implementation

The model is built in MATLAB. The system has different responses for different initial conditions as expected. The initial conditions are upon the stator currents which are represented in d-q axis and directly affect the output power relations.

When MPC is applied with N horizon and dual mode operation for a 0.5 seconds time for 3 different initial conditions and 4 different combinations of R and Q values shown in 2, we obtain solutions seen in figures 8, 9,10 for $T_s = 1e-4$.

Table 2: Cases for MPC

Cases	R	Q
Data1	0.001	C^TC
Data2	1000	C^TC
Data3	0.001	I
Data4	1000	I

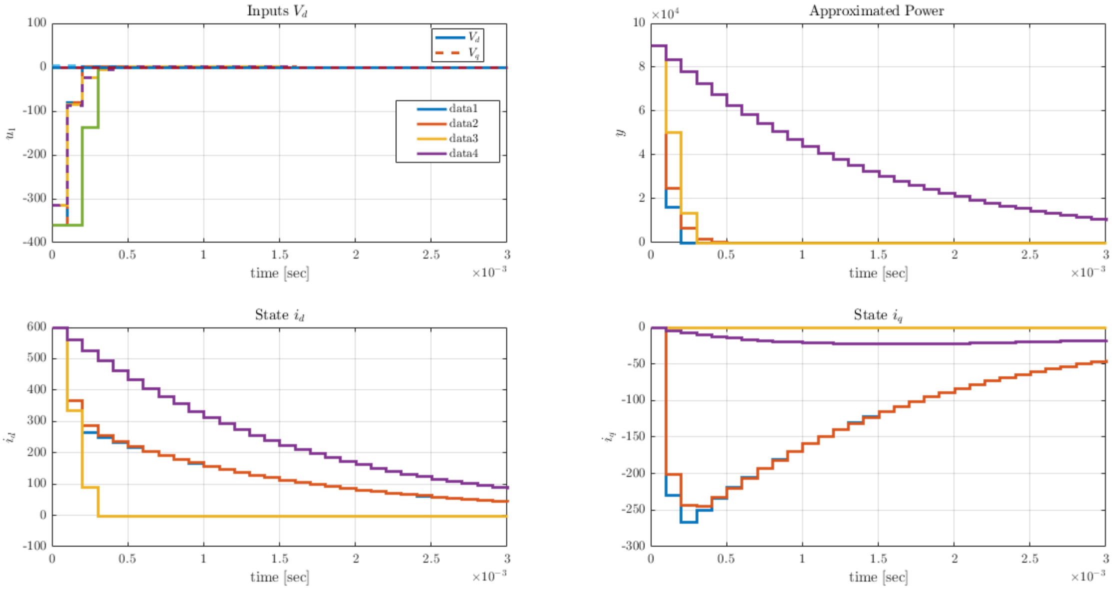

Figure 8: $i_d = 600A$ and $i_q = 0A$ initial condition

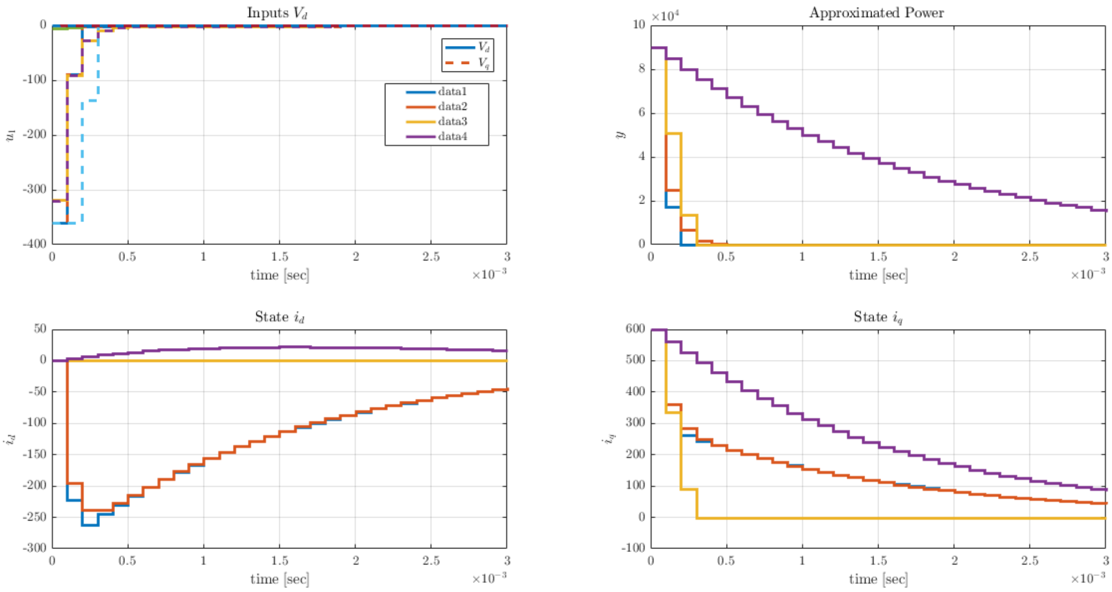

Figure 9: $i_d = 0A$ and $i_q = 600A$ initial condition

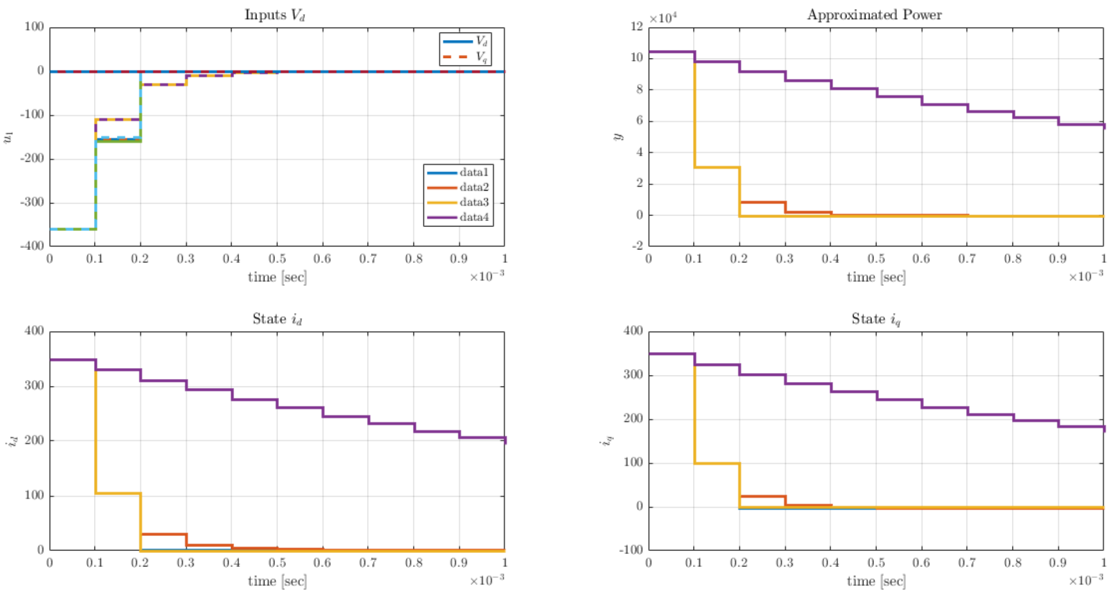

Figure 10: $i_d = 350A$ and $i_q = 350A$ initial condition

Looking at the figures, first of all, it is observed that the system parameters converges to 0 very fast. This is also observed from the eigenvalues of the $A - B * K_{inf}$ such that they lie in unit circle and that the system is stable.

Secondly, we see that the responses are similar for different initial conditions. Yet, when the maximum minimum values for currents switch, wee see that the states behaviour switch as well.

Let's now, make $T_s = 1e-4$ and continue with equal initial conditions 11.

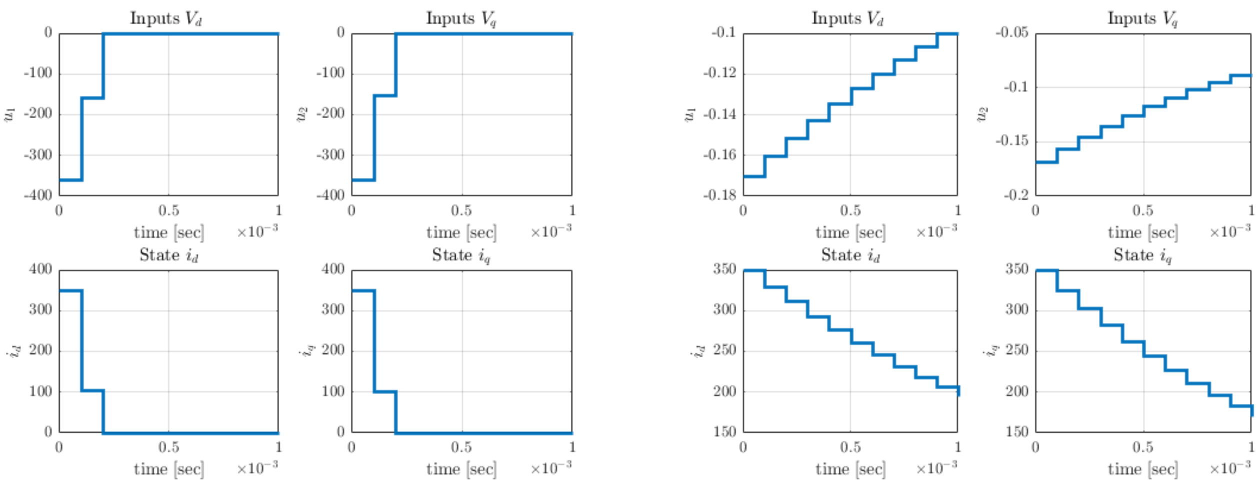

Figure 11: $R = 0.0001$, $Q = I$ and $R = 1000$, $Q = I$ cases for $T_s = 0.0001$

We can clearly see that when put equal weight to the states, if we increase the cost weight R, the input values decrease. But this increases the time for reaching steady state and it takes more steps for the states to reach the desired reference values. It is important to notice that state does not exceed its maximum point and even for small R values, inputs do not reach to instable values. This is good for system performance and we can put more weight on the input cost. Figure 12 shows power response. Here it is important to note that power depends on the grid side dq voltage and current multiplication shown in 3. Therefore, it is assumed that grid voltages are constant and power is directly linear addition of MPC controlled grid currents. Figure 12 shows that for larger R, input is restricted and therefore it takes longer time for the system to reach the desired reference power.

$$P(k) = v_{dg}(k)i_{dg}(k) + v_{qg}(k)i_{qg}(k) \tag{3}$$

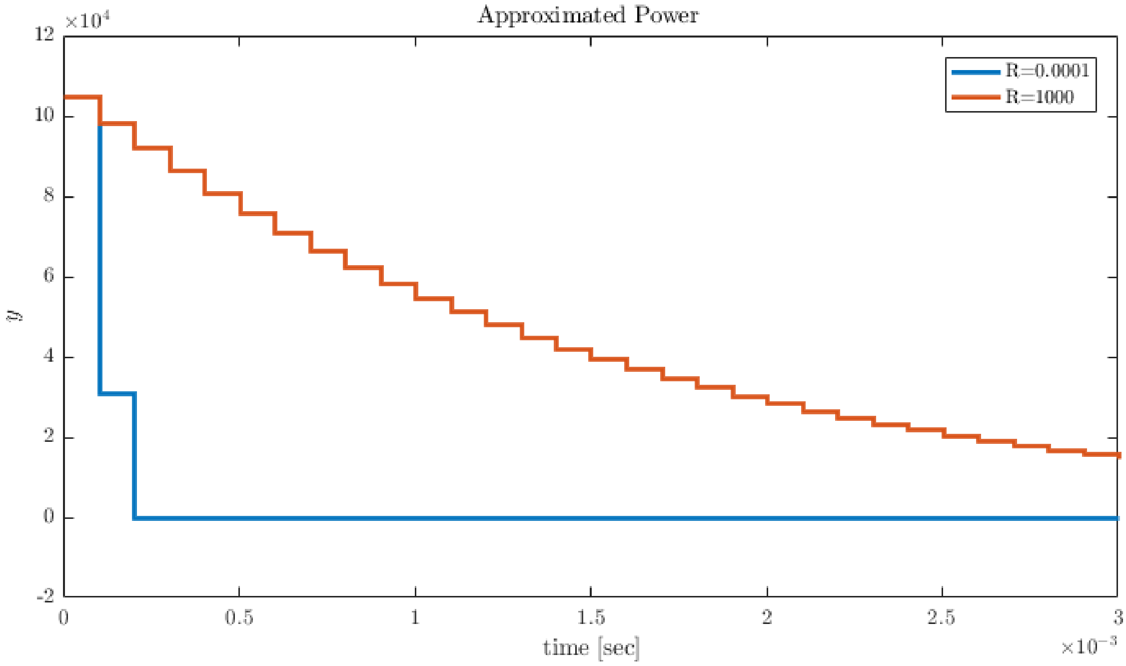

Figure 12: Approximated Power Response

Additionally, we see that the inputs does not exceed the constraint. When the input constraint is changed, it responses as expected. (13)

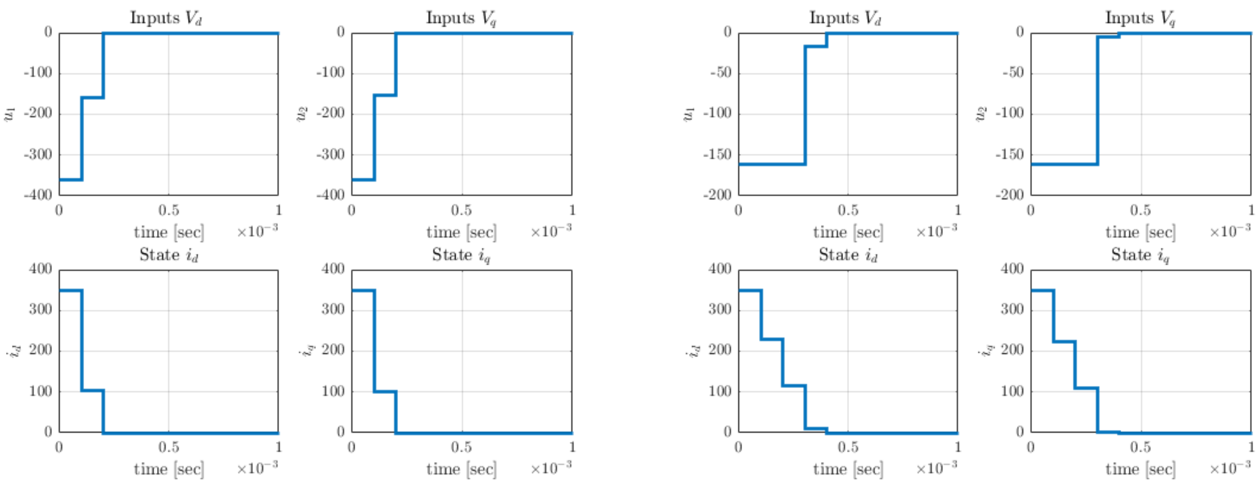

Figure 13: $-360 \leq v_{ds}, v_{qs} \leq 360$, $-160 \leq v_{ds}, v_{qs} \leq 160$

5 Simulink

In this part, implementation of the synchronous motor with MPC is carried. At the beginning only electrical model is used since we only care about the electrical system and using a Matlab function, dare operation had been desired to run within Simulink. This model is also included in the supportive documents being submitted with the report. However, the problem of dare operation being standalone, implementing this operation would be hard and not desired due to its possible indeterminate future outcomes. Hence, a new model is generated examining the inductive motor MPC used in [5],[6].

The induction model and parameters presented and used in [6] is completely different from the ones derived for the synchronous machine used in this project. However, the MPC simulation implementation is fruitfull. Henceforth, it is applied to the synchronous machine as well. The idea behind this MPC modelling is to decrease the cost depending on the states (currents in our case).

We know that there are 8 switching states giving 8 possible state currents. The model has to iterate from 1 to 8 (figure 15)and try each one of the states and predict the outcoming current for that state. Then this current will be deduced from the reference to give the error. Lastly the error will be squared and multiplied with a weighting gain. This operation will be done for both I_d and I_q currents with their weighting factors as shown in 1. This is important since these currents define the active and reactive power.

A synchronous machine can operate as a motor and a generator. The only difference for the state space is the sign for the power and torque [8]. Therefore a model for the motoring operation is built for simplicity and minimising the simulation time. The simulink model is given in figure 14

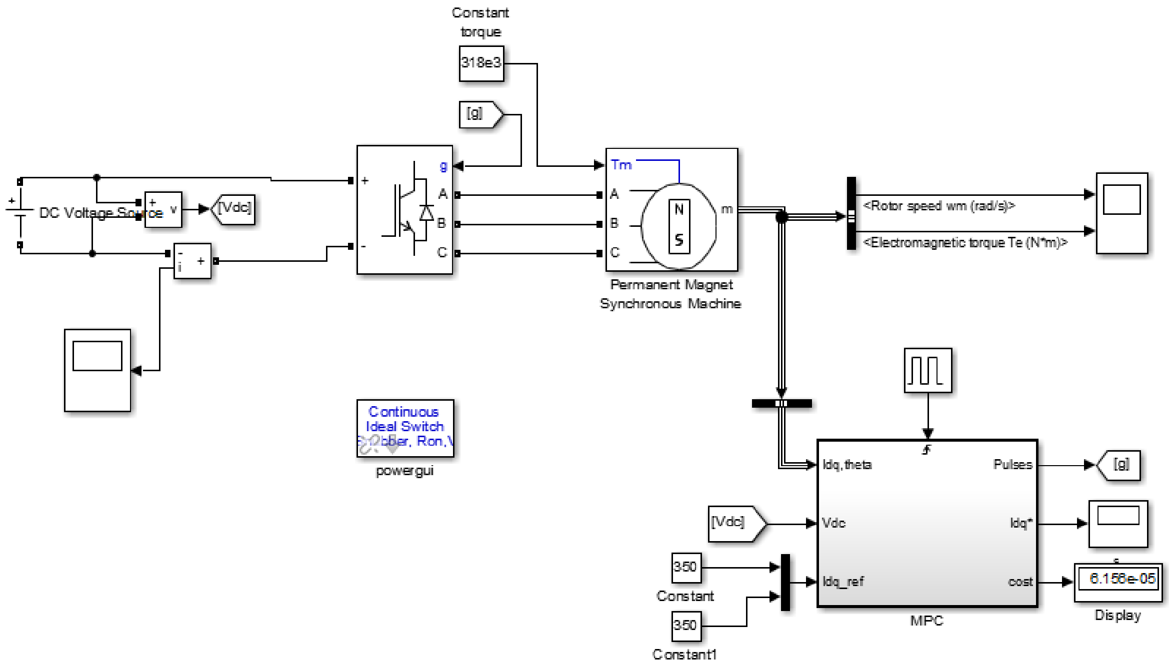

Figure 14: Simulink Model for the proposed Wind Turbine with its parameter set and MPC control applied

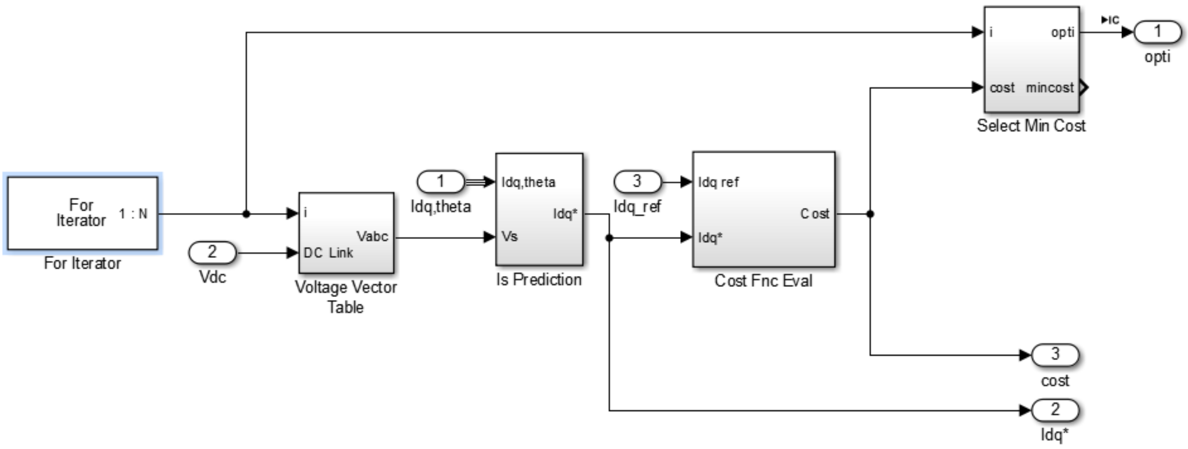

Figure 15: Iteration and cost function calculation for 8 space vector states. The one giving the minimum cost is selected at the end and the corresponding switching sequence is given as gate signal.

In the simulation, it was aimed to maximise the d axis current and minimise the q axis current as in m-file. The weight for the two is given same and small to decrease the cost function. The model output can be seen in figure 16. As expected the currents reach to the reference value after a while. The cost is decreased to $5e - 5 = 5 * 10^{-5}$. It is important to state that fine tuning for the weighting factors is important for a desired operation.

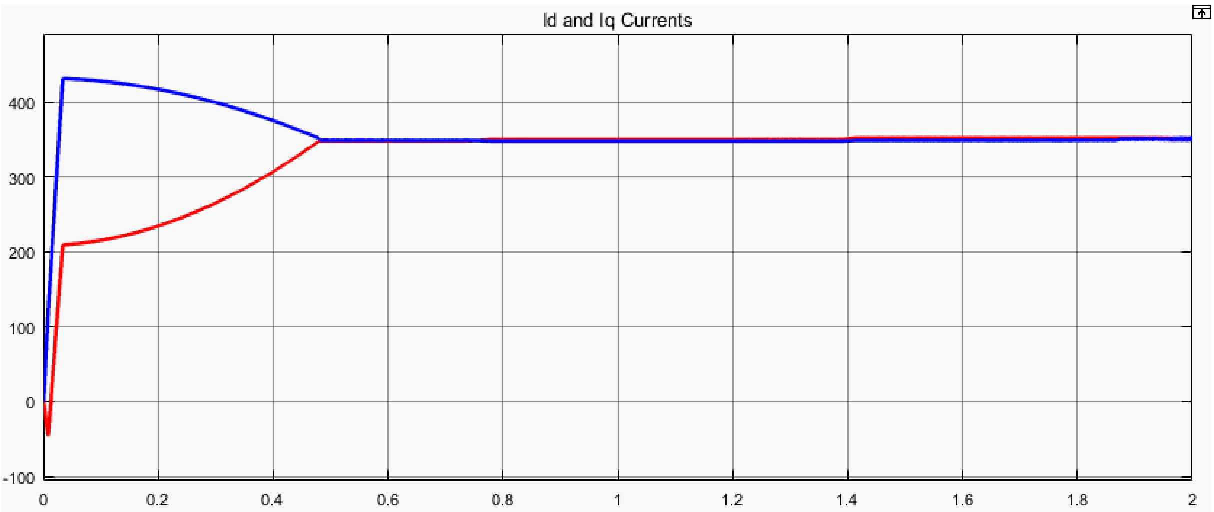

Figure 16: Simulink Model for the proposed Wind Turbine with its parameter set and MPC control applied

6 Conclusion

In this project, a simplified model predictive control is generated both in MATLAB and Simulink with different techniques. The Simulink model verifies the operation conducted in MATLAB. The overall operation range is very broad and only one case is further developped in Simulink.

In this project, I have aimed to take a deeper look in wind turbine mechanical and electrical operation for my further studies. I had the chance of reading many different theses and books from literature, link the topics covered in EE464 on space vector control and EE498 MPC control. It showed me the real meaning and operation of MPC in real plants. The model implemented for this project is open for further improvements and possible corrections and fine tunings.

References

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[7] Sven Creutz Thomsen. Wind turbine control model predictive control for uncertain systems. Ph.d. thesis, Technical University of Denmark, February 2010.

[8] Wu B. Yaramasu W. *MODEL PREDICTIVE CONTROL OF WIND ENERGY CONVERSION SYSTEMS*. IEEE PRESS,WILEY, Hoboken, New Jersey, 2017.

7 Appendix

```
%% Model Parameters
set(groot,'defaulttextinterpreter','latex');
set(groot, 'defaultAxesTickLabelInterpreter','latex');
set(groot, 'defaultLegendInterpreter','latex');
clear all;
%close all;
%%
Vdc=540;
ma=0.8;
wg=61.25;
Ts=1e-3;
tend=0.01;
% Here, the synchronous machine parameters are defined:

ri=0.1;  % Grid side converter harmonic filter resistance
Li= 0.16e-3; % Grid side converter harmonic filter inductance

A11=1-(ri*Ts)/Li;
A12=wg*Ts;
A21=-A12;
A22=A11;

B11=Ts/Li;
B22=B11;
B12=0;
B21=0;
A=[A11 A12; A21 A22];
B=[B11 B12; B21 B22];
v_dg=100;
v_qg=100;
C=1.5*[v_dg v_qg];
D=0;
x0 = [350; 350];
% Optimal control solution for $N = 4$
G = [zeros(2,2) zeros(2,2) zeros(2,2) zeros(2,2); B zeros(2,2) zeros(2,2) zeros(2,2); ...
    A*B B zeros(2,2) zeros(2,2); A^2*B A*B B zeros(2,2); A^3*B A^2*B A*B B];
H = [eye(2); A; A^2; A^3; A^4];
R = 1e4*eye(2);
Q = eye(2); %states vs input
Pinf = dare(A,B,Q,R,zeros(2,2),eye(2) );
Kinf = inv(R+B'*Pinf*B)*B'*Pinf*A;
P = dlyap( (A-B*Kinf)',Q+Kinf'*R*Kinf); % this is lyapunaov eq. for dual mode
Qf = P; % this is the final state after N steps for dual mode
Qbar = blkdiag(Q,Q,Q,Q,Qf); % then with the Q and Qf at hand calculated for step k
Rbar = blkdiag(R,R,R,R);
M = G'*Qbar*G + Rbar;
umin = -360;
umax =360;
lb = [umin;umin;umin;umin];
ub = [umax;umax;umax;umax];
% Apply MPC steps
xVec(:,1) = x0;
yVec(1) = C*x0;
uVec = [];
for kk = 1:1:tend/Ts
    alpha = G'*Qbar*H*xVec(:,kk);
    Usol = quadprog(M,alpha',[],[],[],[],lb,ub);%% MPC here with every changing state alpha
    % changes and this makes the next state's quadratic cost function with N horizon
    uVec(:,kk) = Usol(1:2);
    xVec(:,kk+1) = A*xVec(:,kk) + B*uVec(:,kk);
    yVec(kk+1) = C*xVec(:,kk+1);
end
```

Figure 17: For the proposed Wind Turbine, Electrical Model Parameters and MPC Code