Model Predictive Control of a Wind Driven Induction Generator Connected to the Utility Grid

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Abstract: This study presents an adaptive control for interfacing Wind Energy Conversion System (WECS) to utility grid based on Model Predictive Control (MPC). The proposed system mainly consists of a wind turbine which drives an induction generator. The generator is connected to the utility grid through DC-Link. The main control objective aims to regulate the DC link voltage and to track and extract maximum available wind power. This is accomplished via controlling the firing angles of the rectifier and the inverter. The MPC controller is based on the minimization of a cost function of voltage and power errors while respecting the given constraints. The performance of the wind generation system with the proposed MPC controller has been tested through a step change in reference input power. Simulation results confirm that good dynamic performance of the proposed wind energy scheme has been achieved.

Key words: Model predictive control, wind energy, induction generator, WECS, voltage, Egypt

INTRODUCTION

Nowadays, the total installed wind power capacity as well as the average rated power per wind mill is constantly increasing. In many countries, wind-power experienced a rapid growth during the past years and contributes nowadays considerably to the overall electricity production. The squirrel cage induction machine is ideally suited for use in wind energy applications as it requires low maintenance and is built robustly to withstand severe operating conditions (Bohmann et al., 1996).

Various control strategies have been proposed for regulating grid voltage and achieving optimal output power of the turbine. In some schemes, the wind turbine drives an induction generator connected to grid through a static converter (Miller et al., 1997; Abdin and Wilson, 2000). Other control schemes use search methods that vary the speed until optimal power is obtained (Spee et al., 1995; Simoes et al., 1995). However, these techniques have the difficulty of tracking the wind which will cause additional stress on the shaft.

Recently, advanced control tehniques, which were applied successfully on the machine drives have been proposed for regulating the wind power in a grid connected wind energy conversion scheme. In the first approach (Thiringer and Linders, 1993) the dead beat control of output power was proposed. However, the knowledge of wind speed must be necessary for controller implementation.

In other approach (De Battista et al., 2000; De Battista and Mantz, 2004) the sliding mode technique has been employed in a variable structure controller for regulating the output power. The proposed sliding mode controller has the advantages of robustness against parameter uncertainties as well as wind disturbances. However, an inevitable chattering resulting from the switching of the control structure still exist. Moreover, the wind estimation would be needed in (De Battista et al., 2000), while a speed sensor must be existed in (De Battista and Mantz, 2004) to measure the rotor speed.

In (Godoy et al., 1997) a fuzzy logic based intelligent controller has been used extensively to optimize efficiency and enhance performance of a variable speed wind generation system. This controller has the advantages that it does not require the mathematical model of the system besides the insensitivity to external disturbance and erroneous information. However this system has two drawbacks. First, the operating point oscillates largely with the change in wind speed. Second, a speed sensor is needed to provide the speed signal.

During the past decades, the MPC control theory has been widely extolled in the petrochemical, lesser extent, the process industries, DC drives (Zhuang, 2000) and power system (Tavahodi, 2007; Wang et al., 2006) because constraints can be implicitly included in the problem formulation. In MPC, at each sampling time, based on current measurements, MPC uses an explicit process model and information about operating and physical constraints to compute optimal process inputs

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so as to optimize future plant behavior over a prediction horizon. The first portion of this optimal control sequence is then implemented to the plant and the procedure is repeated at the next sampling time (Maciejowski, 2002).

This study considers the application of constrained linear MPC controller to interface the wind energy system to the utility grid. The main objective of the proposed controller are tracking maximum available wind power and regulating the dc link voltage. The MPC controller provides the signals necessary for operating the rectifier and inverter switches. Different constraints are imposed on the system states to keep them within reasonable values.

The feasibility and effectiveness of the wind energy generating scheme together with the proposed MPC controller have been demonstrated through computer simulations. Simulation results have proved that the proposed controller can give better overall performance.

System description: Figure 1 shows a wind energy system connected to the utility grid via an asynchronous AC-DC-AC link. It consists of a vertical axis wind turbine, driving a self excited induction generator. The asynchronous link consists of a six pulse line commutated converter, a smoothing reactor and a six pulse line commutated inverter.

This system essentially converts the variable voltage variable frequency at the induction generator terminals to constant voltage constant frequency at the grid terminals. The DC link decouples the induction generator and the utility systems such that each system operates at its own frequency. This enables the induction generator to operate over a wide speed range.

The flow of power across the DC link can be controlled by adjusting the firing angles of the controlled rectifier and the inverter.

MATERIALS AND METHODS

Small signal linearized model: The non-linear dynamic model of the wind generation system can be desribed in the d-q synchronously rotating reference frame by the following nine differential Eq. 1-9 (Abdel-Twab *et al.*, 2006):
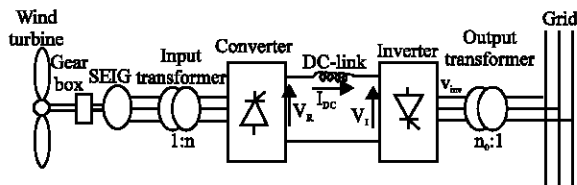

Fig. 1: Shematic diagram of the proposed wind energy system

$$pi_{qs} = -R_sA_1i_{qs} - (\frac{i_{qs} + \frac{2\sqrt{3}}{\pi}nI_{DC}\sin\alpha_R}{C_0v_{ds}} \qquad (1)$$
$$+ A_2\omega_mL_m)i_{ds} + R_rA_2i_{qr} - A_1\omega_mL_ri_{dr}$$

$$pi_{ds} = (\frac{i_{qs} + \frac{2\sqrt{3}}{\pi}nI_{DC}\sin\alpha_R}{C_0v_{ds}} + A_2\omega_mL_m)i_{qs} \qquad (2)$$
$$- R_sA_1i_{ds} + R_rA_2i_{dr} + A_1\omega_mL_mi_{qr} - A_1v_{ds}$$

$$pi_{qr} = R_sA_2i_{qs} + A_2\omega_mL_si_{ds} - A_3i_{qr}$$
$$+ (-\frac{i_{qs} + \frac{2\sqrt{3}}{\pi}nI_{DC}\sin\alpha_R}{C_0v_{ds}} + A_1\omega_mL_s)i_{dr} \qquad (3)$$

$$pi_{dr} = -A_2\omega_mL_si_{qs} + R_sA_2i_{ds}$$
$$+ (\frac{i_{qs} + \frac{2\sqrt{3}}{\pi}nI_{DC}\sin\alpha_R}{C_0v_{ds}} - A_1\omega_mL_s)i_{qr} \qquad (4)$$
$$- A_3i_{dr} + A_2v_{ds}$$

$$p\omega_m = (-f\omega_m + PT_m$$
$$+ 1.5P^2L_m(i_{qs}i_{dr} - i_{ds}i_{qr}))/J \qquad (5)$$

$$pv_{ds} = \frac{i_{ds} - \frac{2\sqrt{3}}{\pi}nI_{DC}\cos\alpha_R}{C_0} \qquad (6)$$

$$pI_{DC} = (-R_{DC}I_{DC} + \frac{3\sqrt{3}}{\pi}nv_{ds}\cos\alpha_R$$
$$+ \frac{3\sqrt{3}}{\pi}v_{inv}\cos\alpha_I - \frac{3x_{ci}}{\pi}I_{DC})/L_{DC} \qquad (7)$$

$$p\alpha_R = V_{ref} - V_R = V_{ref} - \frac{3\sqrt{3}}{\pi}nv_{ds}\cos\alpha_R \qquad (8)$$

$$p\alpha_I = P_{ref} - P_O = P_{ref} - (\frac{3\sqrt{3}}{\pi}nv_{ds}\cos\alpha_R)I_{DC} \qquad (9)$$

Where:

v_{ds}	=	d-axis stator voltage
i_{ds}, i_{qs}	=	d-q stator currents
i_{dr}, i_{qr}	=	d-q rotor currents
R_s, R_r	=	Stator and rotor resistances per phase
L_s, L_r, L_m	=	Stator, rotor and magnetizing inductances
C_0	=	Self excitation capacitance/phase
ω_m	=	Electrical angular rotor speed
J	=	Moment of inertia

f	=	Friction coefficient
p	=	Differential operator d/dt
α_R, α_I	=	Firing angles of the converter and inverter
I_{DC}	=	DC link current
v_{inv}	=	Inverter output voltage
x_{ci}	=	Commutating inverter reactance
L_{DC}	=	DC link inductance
R_{DC}	=	DC link resistance
V_{ref}, V_R	=	Reference and actual rectifier output voltages
P_{ref}, P_0	=	Reference and actual output powers, $A_1 = L_r/(L_sL_r\text{-}L_m^2)$, $A_2 = L_m/(L_sL_r\text{-}L_m^2)$, $A_3 = R_r(1+A_2L_m)/L_r$

The MPC controller proposed here for regulating the voltage and power output of the system under study is based on the state space linear model.

Therefore, the nonlinear dynamic model of the complete wind energy conversion system is linearized arround an operating point. The linearized model takes the following state matrix form:

$$px = Ax + Bu , y = Cx$$

Where:

$$x = [\Delta i_{qs} \quad \Delta i_{ds} \quad \Delta i_{qr} \quad \Delta i_{dr} \quad \Delta\omega_s \quad \Delta v_{ds} \quad \Delta I_{DC} \quad \Delta\alpha_R \quad \Delta\alpha_I]^T$$

$$u = [\Delta V_{ref} \quad \Delta P_{ref}]^T$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T$$

and A = $[a_{ij}]$ is a 9×9 matrix containing the system parameters.

Model predictive control: MPC is a generic term for computer control algorithms that utilizes an explicit process model to predict future response of the plant.

An optimal input is computed by solving an open-loop optimal control problem over a finite time horizon, i.e., for a finite number of future samples. The number of samples one looks ahead is called the prediction horizon Np. In some MPC formulations a difference is made between prediction horizon and control horizon Nu. The control horizon is then the number of samples that the optimal input is calculated for. With a shorter control horizon than prediction horizon the complexity of the problem can be reduced. From the calculated input signal only the first element is applied to the system. This is done at every time step. The idea is

thus to go one step at a time and check further and further ahead. The method can be described as repeated open-loop optimal control in feedback fashion (Allgower *et al.*, 2004). In an MPC-algorithm there are three important elements:

Model used for prediction: The model is in most MPC-formulations today given on discrete time state space form:

$$x(k+1) = Ax(k) + Bu(k) + B_{MD}u_{MD}(k) \qquad (10)$$
$$y(k) = Cx(k)$$

Where:

x(k)	=	State vector
u(k)	=	Input vector
$u_{MD}(k)$	=	Vector of measured disturbances, i.e., input signals that are not calculated by the controller
y(k)	=	Output vector

Cost function: The cost function is designed differently depending on what to minimize. Common is a quadratic cost function which penalizes both deviation from a state reference and rapid changes in the control signal:

$$\min \left(x_{N_p} - x_{ref, N_p}\right)^T S\left(x_{N_p} - x_{ref, N_p}\right)$$
$$+ \sum_{i=0}^{N_p-1}\left[\left(x_i - x_{ref,i}\right)^T Q_x\left(x_i - x_{ref,i}\right) + \Delta u_i^T Q_u \Delta u_i\right] \qquad (11)$$

Where:

$$\Delta u_i = u(k+i) - u(k+i-1)$$

A penalty on Δu_i punishes rapid changes in the input signal, which can be used to reduce oscillations. According to a penalty on rapid changes in the input signal also introduces integral action. However this is coupled to the prediction horizon-stationary errors can appear even if integral action is introduced via a penalty on Δu_i if the prediction horizon is not long enough.

In the cost function stated above, the prediction horizon (N_p) and the control horizon (N_u) are the same. Instead of a shorter control horizon there is a penalty on x_{N_p}, which plays a similar role. MPC-toolbox, which will be used for implementation in Simulink, uses the formulation: where, N_u are distinct from N_p. Matrices S, Q_x and Q_u are weight matrices who decide the penalty on each term in the cost function. Most effort is put on minimizing the term with largest penalty.

Constraints: Desired to easily solve the MPC problem is a so called Quadratic optimization Problem (QP). A QP is

a convex problem, i.e. if a solution is found uniqueness is guaranteed. To get a QP the constraints need to be linear. They are thus on the form:

$$x_o = given$$
$$u_{min} \le u_i \le u_{max,} \quad i = 0,.....,N_p - 1 \qquad (12)$$
$$y_{min} \le W x_i \le y_{max,} \quad i = 1,.....,N_p$$

where the matrix W forms the output states.

Optimization problem and algorithm: The optimization vector is:

$$U = \left[u^T(k),...,u^T(k+N_p-1) \right]^T$$

If a shorter control horizon than prediction horizon is used, it is assumed that u(k+i) = u(k+N_u-1)for all i≥N_u. The problem now needs to be rewritten in terms of U only. This is in principle straightforward since:

$$x(k) = A^k x(0) + \sum_{j=0}^{k-1} A^{k-1-j} (Bu(j) + B_{MD} u_{MD}(j)) \quad (13)$$

Finally the optimization problem becomes:

$$U_{min} \le U^T HU + h^T U \qquad (14)$$

Where:
H   =   The matrices
Vector h   =   Build up by x_{ref}, u_{ref}, x_0, Q_x, Q_u, S,A,B and C

The MPC-algorithm can now be summarized as:

- Measure the current state x(k) or estimate it using an observer
- Solve the k:th optimization problem to obtain

$$U = \left[u^T(k),...,u^T(k+N_p-1) \right]^T$$

- Apply u(k) to the system
- Update time k = k+1 and repeat from step 1

Implementation scheme: The objective of this control is to regulate the terminal voltage at the rectifier output and minimize the deviation between the actual and reference voltages at the rectifier terminal. Also, Tracking maximum available wind power (to fully utilize the available wind energy) at any given wind speed that by minimizing the deviation between the actual and reference powers at the inverter terminal. The cost function will have the following appearance:

$$J = \sum_{i=1}^{N_p} \left[\left(V_{Rref,i} - V_{R,i} \right)^T W_v \left(V_{ref,i} - V_{R,i} \right) \right]$$
$$+ \sum_{i=0}^{N_p-1} \left[\left(P_{ref,i} - P_o \right)^T W_p \left(P_{ref,i} - P_o \right) + \Delta u_{p,i}^T W_u \Delta u_{p,i} \right] \qquad (15)$$

Where:

$$\Delta u_{p,i} = u_{p,i} - u_{p,i-1}$$

the constraints are chosen such that, the inverter output power is normalized to be between 0 and 1, where 0 corresponds to wind cuttoff low speed at blade angle 15° and 1 corresponds to wind cutoff high speed at zero 0° blade angle. Thus,

$$u_{min} = 0 \le u_p \le 1 = u_{max}$$

The constraints imposed on the control signal are hard, whereas the constraints on the states are soft i.e., small violations can be accepted. The constraints on the states are chosen such that to guarantee signals stay at physically reasonable values as follows:

$$x_{min} = \begin{pmatrix} 6 \\ 0.5 \\ 0 \\ 0.5 \\ 270 \\ 80 \\ 0.8 \\ 0 \\ 100 \end{pmatrix} \le \begin{pmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{dr} \\ \omega_m \\ V_{ds} \\ I_{DC} \\ \alpha_R \\ \alpha_I \end{pmatrix} \le \begin{pmatrix} 9 \\ 1.2 \\ 0.1 \\ 1.5 \\ 380 \\ 150 \\ 1.5 \\ 60 \\ 180 \end{pmatrix} = x_{max}$$

In the study, the states are chosen to be the perturbations in stator and rotor current components, speed, stator voltage, DC current, rectifier and inverter firing angles. The stator current components are chosen to be the only output measured signals. The Kalman filter estimator is used to drive the state estimation:

$$x = [\Delta \hat{i}_{qs} \quad \Delta \hat{i}_{ds} \quad \Delta \hat{i}_{qr} \quad \Delta \hat{i}_{dr} \quad \Delta \hat{\omega}_m \quad \Delta \hat{v}_{ds} \quad \Delta \hat{I}_{DC} \quad \Delta \hat{\alpha}_R \quad \Delta \hat{\alpha}_I]^T$$

The block diagram of the wind energy conversion system with the proposed MPC is shown in Fig. 2. The entire system has been simulated using the Matlab/Simulink software package. The specifications of the system used in the simulation procedure are listed in appendix.
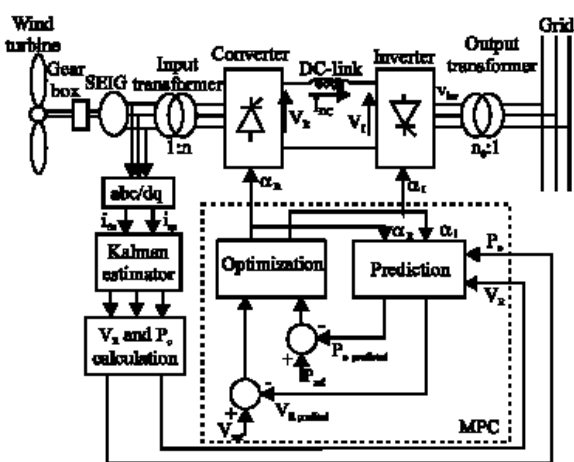
Fig. 2: Block diagram of the wind energy conversion system with the proposed MPC Controller

RESULTS AND DISCUSSION

The wind generation system with the proposed MPC controller will be tested in two different configurations: reference tracking and robustness against parameters variation.

Reference tracking: The performance of the proposed system has been tested with a step change in wind speed. Thus, the wind speed is assumed to vary abruptly from 7-8 m sec^{-1} at t = 2 sec. This means that the power reference increases from 350-400 watts (at blade angle = 0°). Figure 3 shows the dynamic response of the stator current, rotor current and rotor speed of the induction generator, firing angles for both rectifier and inverter, reference and actual rectifier output voltages, reference and actual inverter output powers and DC link current. Simulation waveforms may be interpretted as follows:

As the wind velocity increases from 7-8 m sec^{-1} the mechanical power by the wind turbine increases also and the the induction generator will be accelerated. As the rotor speed increases, the induction generator terminal voltage tends to increase. Hence, the MPC controller will increase the firing angle of the rectifier in order to keep the DC link voltage at the specified level. Also, to track and extract maximum available wind power, the inverter power output should be correspondingly increased. Therefore, the MPC decreases the inverter firing angle in order to track the change of the wind power.

As the voltage error increases, the closed loop adjusts the rectifier voltage causing the firing angle to increase untill this error disappears.

The power closed loop adjusts the inverter firing angle untill the actual power is equal to the reference one. The
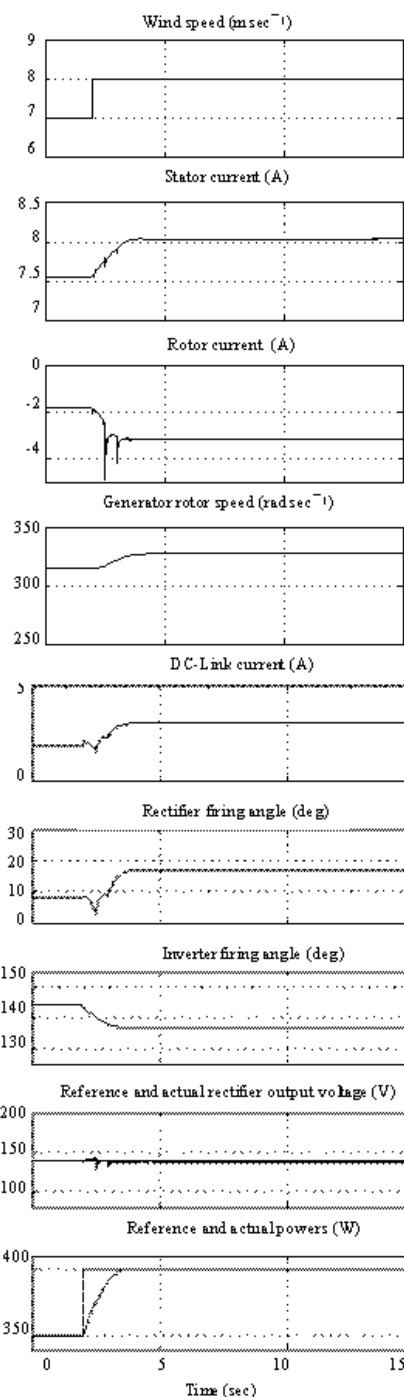

Fig. 3: Dynamic response of the proposed scheme to a step change in wind speed assuming nominal parameters

DC link current increases to satisfy the power requirement. It has been noticed in the Fig. 3 that the actual inverter output power tracks accurately the reference one with zero steady state error and <1 sec rise
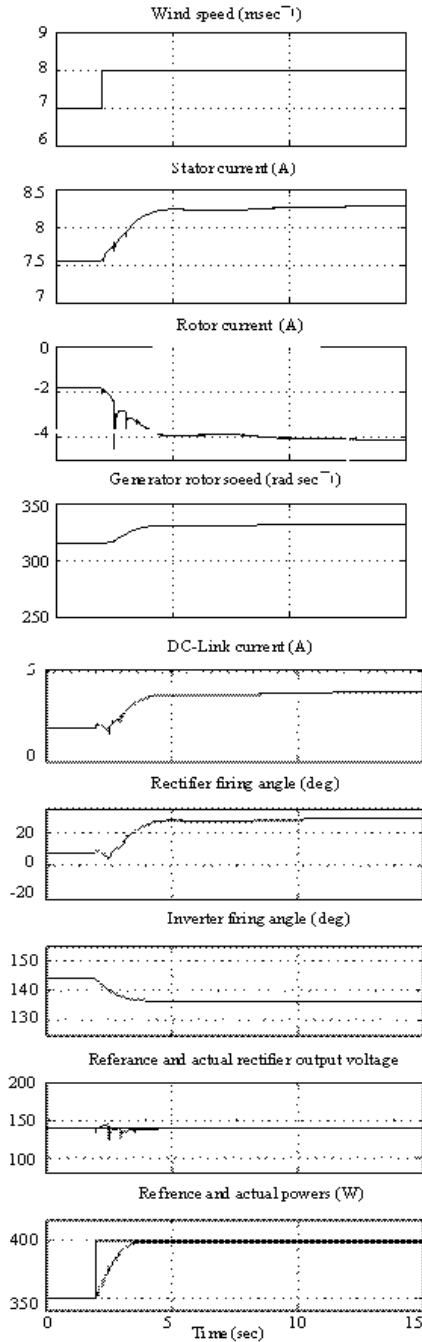
Fig. 4: Performance of the proposed scheme assuming detuned parameters

time. On the Other hand, an overshoot with amplitude <1.0% has been noticed in the response of the actual voltage output from the rectifier but it dies fastly.

Robustness: The Fig. 3 reports also that the steady state between the actual and reference voltages is equal to about 0.1%. Since the concern is also in robust stability

against various model uncertainties, some system parameters have been changed in the following ways:

- The stator and rotor resistances are increased by 20%
- The magnetizing inductance is decreased by 10%
- The moment of inertia is increased by 15%

For perturbed system the responses are shown in Fig. 4. Again, the MPC controller adjusts the firing angles of the rectifier and inverter to track the reference voltage and power while respecting the constraints imposed on the states. It should be seen that the system is robustly stable in spite of parameters variation.

CONCLUSION

In this study, the MPC controller has been applied successfully for a wind driven generation system. The proposed system mainly consists of a wind turbine which drives an induction generator connected to the utility grid through DC-Link. The main control objective aims to calculate the optimal rectifier and inverter firing angles for regulating the DC link voltage and to tracking and extracting maximum available wind power. At the same time, the controller respects the constraints imposed on the states and control signal.

The performance of the wind generation system with the proposed MPC controller has been tested through a step change in wind speed with nominal and detuned parameters. Simulation results confirm that good dynamic performance of the proposed wind energy scheme has been achieved.

APPENDIX

System parameters
Wind turbine
Rating: 1kw, 450 rpm (low speed side) at $V_w = 12$ m s^{-1}
Size: Heigh $= 4$ m, Equator radius $= 1$ m, Swept area $= 4$ m^2, $\rho = 1.25$ kg m^{-2}.

Induction machine
Rating: 3-phase, 2 kw, 120 V, 10 A, 4-pole, 1740 rpm.

Parameters: $R_S = 0.62\Omega$, $R_r = 0.566\Omega$, $L_S = L_r = 0.058174$ H, $L_m = 0.054$ H, $J = 0.0622$ kg m^{-2}, $f = 0.00366$ Nm/rad/sec.

DC link: $R_{DC} = 1.7\Omega$, $L_{DC} = 0.15$ H.

Self excitation capacitor: Rating: 176 μf/phase, 350 V, 8 A.

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