RESEARCH PAPER

Continuous Control Set Model Predictive Control (CCS-MPC) of A Three-Phase Rectifier

Mohammad Shadnam Zarbil¹, Masood Saeidi², Abolfazl Vahedi³, Hossein Azizi Moghaddam⁴

¹Department of Electrical, College of Engineering, Iran University of Science and Technology (IUST), Tehran, Iran.
²Department of Electrical, College of Engineering, Iran University of Science and Technology (IUST), Tehran, Iran.
³Department of Electrical, College of Engineering, Iran University of Science and Technology (IUST), Tehran, Iran.
⁴Department of Electrical Machine Research Group, Niroo Research Institute (NRI), Tehran, Iran.

A B S T R A C T:
The rectifier is one of the popular power electronic converters in industrial applications such as in the railway and power supply systems. In this paper, a three-phase controllable rectifier is considered and the continuous control set model predictive controller (CCS-MPC) is designed. By considering system dynamic response, the proper criteria to select the sampling time, prediction horizon and control horizon is proposed. By using these criteria, the tradeoff between computational burden and system performance dynamic is made. When using the CCS-MPC controller, the rectifier and grid performance such as total harmonic distribution (THD) and power factor (PF) have acceptable value. The simulation results are validated by using MATLAB/SIMULINK software.

KEY WORDS: Rectifier; Predictive control; Mathematical Modeling; Total Harmonic Distortion; PI Tuning.

INTRODUCTION:

Todays, power electronic converters have become the most important controllable device in power systems (Huang, 2017). The main feature of these converters which makes it practical in the power system components, is their high controllability. In the past, due to the low level of semiconductor manufacturing technology, the converters switching speed was low that making using them impossible or very slow.

Nowadays, thanks to semiconductor manufacturing improvements, these converters can be used in high speeds and capacities, so today, in the power system and industrial application these converters are used in the high level of power, at the scale of GIGAWATT and with frequency up to 400 kHz (Besselmann et al., 2016). In order to exploit the capabilities of this converter, using new control and new switching methods are necessary.

In (Ginn et al., 2015; Lucia et al., 2018), advantages of control methods of power electronic converters have been presented and various methods for control these converters have been provided. However, the usage of the linear controller such as P or PI is the main weakness of these references. In the case of mentioned references, control algorithms are the same, but...
they differ in their switching methods. Due to the existence of uncertainties and nonlinear behavior in the system, using the linear controller theory is not recommended. So, researchers have tried to use new control methods to solve the linear controller theory problems. To overcome these problems, in (Kashif and Saqib, 2016; Yang et al., 2017; Xiong et al., 2018), the use of intelligent control methods such as neural networks, fuzzy, and sliding mode control has been proposed. In spite of creating computational burden and being complex in both design and operation having many defects, using these controllers can indeed overcome the disadvantage of ordinary linear controllers but linear controllers have still the first priority in power electronic converters. With the introduction of predictive control methods, this control method has gradually been used in the industrial application. The first model predictive control algorithm has been implemented in the chemical industry. With the advancement of computer processors, the processing speed has been increased dramatically and providing the ability to implement predictive control algorithms in most industries (Hrovat et al., 2012). According to the discrete nature of the power electronic converters, the use of predictive control algorithm in these systems has been suggested in (Bordons and Montero, 2015; Vazquez et al., 2017). Today, all controllers are implement digitized, but it is necessary to select the suitable sampling time for these systems. The importance of selecting the appropriate sampling time in the MPC algorithm is discussed in (Garriga and Soroush, 2010).

In this paper, a modified CCS-MPC for a three-phase rectifier is designed. According to the system dynamic response, a criterion is proposed for selecting the prediction and control horizon in the MPC controller. This paper is organized as follows. The mathematical model of the three-phase controllable rectifier is reviewed in Section 2. Model predictive controller design of rectifier is presented in Section 3. The simulation results are presented in Section 4. Some conclusions are given in Section 5.

1. MATHEMATICAL MODEL OF THREE-PHASE CONTROLLABLE RECTIFIER

The state space method is used to model this converter. Dynamic elements are selected as system state variables; therefore, capacitor voltage and grid current are selected as rectifier system state variables (Santoyo-Anaya et al., 2018). With this assumption, the state equations of the system are given as follows:

\[
\frac{di_a(t)}{dt} = \frac{-R}{L}i_a - \frac{1}{L}v_{ra}(t) + \frac{1}{L}v_a(t) \quad (1)
\]

\[
\frac{di_b(t)}{dt} = \frac{-R}{L}i_b - \frac{1}{L}v_{rb}(t) + \frac{1}{L}v_b(t) \quad (2)
\]

\[
\frac{di_c(t)}{dt} = \frac{-R}{L}i_c - \frac{1}{L}v_{rc}(t) + \frac{1}{L}v_c(t) \quad (3)
\]

\[
I_{dc}(t) = I_{dc_a}(t) + I_{dc_b}(t) + I_{dc_c}(t) \quad (4)
\]

\[
\frac{d}{dt}v_{dc}(t) = \frac{1}{c}I_{dc}(t) - \frac{1}{cR_L}v_{dc}(t) \quad (5)
\]

\[
I_{rabc} = \frac{1}{2}m_i(t) \ast v_{dc} \quad (6)
\]

\[
v_{rabc} = v_{abc} - ZI_{rabc} \quad (7)
\]

\[
i_{rabc} = \frac{1}{2}m_i(t) \ast I_{dc} \quad (8)
\]

In the above equations, \(i_a, i_b, i_c\) are currents of the grid, \(v_{ga}, v_{gb}, v_{gc}\) are voltages of grid, \(v_{dc}\) is the rectifier output voltage, \(C\) is capacitance of the capacitor, \(m_i\) is modulation index, \(I_{dc}\) is the current of the rectifier, \(R, L\) and \(Z\) are resistance, inductance, and impedance of the grid respectively. By using the above equations, the model of the system is written as follows:

\[
\frac{di_a(t)}{dt} = \frac{-R}{L}i_a - \frac{1}{L}v_{ra}(t) + \frac{1}{L}v_a(t) \quad (9)
\]

\[
\frac{di_b(t)}{dt} = \frac{-R}{L}i_b - \frac{1}{L}v_{rb}(t) + \frac{1}{L}v_b(t) \quad (10)
\]

\[
\frac{di_c(t)}{dt} = \frac{-R}{L}i_c - \frac{1}{L}v_{rc}(t) + \frac{1}{L}v_c(t) \quad (11)
\]

In Eqs. (9-12) with considering that grid currents have dependency with together, therefore, one phase current and capacitor voltage are selected as state variables and grid voltages are system input variables respectively. In the state equations, there are some nonlinear terms such as \(\frac{(i_a + i_b + i_c)}{cv_{dc}}\) and \(m_i(t)\), therefore for linear analyses using 10 kw rectifier parameter Tab.1 and using the Taylor expansion method can be linearize of Eqs. (9-12) around the nominal operation point \((i_{abc} = 26.18, v_{dc} = 400, v' = 19.09)\), transfer function is calculated as:

ZANCO Journal of Pure and Applied Sciences 2019
$$H(s) = \frac{v_{dc}}{m_1}(s) = \frac{2.8286(s + 175100)}{(s + 51.17)(s + 125.7)}$$  \hspace{1cm} (13)$$

2. MODEL PREDICTIVE CONTROL DESIGN FOR THE RECTIFIER

Because of nonlinear behavior and parameter uncertainties in power electronic converters, by using the new controller, the defects of linear controllers are eliminated. The model predictive control algorithm is one of the best options for using in power electronic converter applications. The rectifier control system is shown in Fig.2.

2.1 Model Predictive Control Algorithm

Model predictive control algorithm generates a proper signal to control the DC output voltage. MPC controller is implemented in 4 forms which are: DMC, AMC, PFC, and GPC (Thomas, 2014). In this reference, a full comparison between 4 forms of the MPC controller is taken and its result is that using GPC format for unstable, non-minimum phase and system with very small zero is appropriate. Therefore in this paper, the GPC form for MPC implementation is used. For nonlinear effects minimizing, Using of MPC is recommended, therefore in this paper, it is applied to the rectifier system. The MPC controller can be formulated as Eq.(20), a control signal can be produced, with minimization of the cost function J:

$$J(N_1,N_p,N_c) = \sum_{j=N_1}^{N_p} \delta(j)[\hat{y}(t + j|t) - w(t + j)]^2 + \sum_{j=1}^{N_c} \lambda(j)[\Delta u(t + j - 1)]^2$$  \hspace{1cm} (20)

Where, $N_p$ is prediction horizon, $N_c$ control horizon, $N_1$ model delayed, $\Delta u$ control signal, $\hat{y}(t)$ model output, $w(t)$ reference set point and $\delta(j)$ and $\lambda(j)$ are the weight factors (Garriga and Soroush, 2010).

2.2 Tuning of the Model Predictive Controller Parameter

Choosing the appropriate values for the controller parameters in the cost function can be effective in reducing the computation burden. Therefore, with proper selection of these parameters, optimal control signals can be generated which improves the power electronic converters performance and efficiency. The values for the prediction horizon and sample time should be selected according to the system specification (Garriga and Soroush, 2010). If the cost function doesn't have any constraints, by applying optimization methods, the cost function can be optimized by conventional method but in case of constrained MPC controller design, complex minimization method such as active set and Gauss-Seidel method are applied (Peterson et al., 1992; Dai et al., 2017). The MPC controllers are implemented in both schemes of finite control set (FCS-MPC) and continuous control set (CCS-MPC). The idea of using FCS-MPC is referred as to the natural discrete property of power electronic converter hence by applying the model prediction, the switches finite state is predictable (Mendez, Sbarbaro and Espinoza, 2016). This method has advantages, such as lack of need for modulators, the simple implementation, and the intuitive understanding algorithm. Having variable switching frequency, system response fluctuations and the steady-state error in the system output response are considered as its disadvantage. Another scheme for implementing the MPC controller is acquired via the CCS approach. In this method, the MPC controller generates an appropriate reference signal which is used in SPWM or SVM modulators. Some of the CCS-MPC advantages are given as constant switching frequency, the possibility of eliminating the steady-state error, less sampling time and designed controller with proof of the possibility of stability moreover using long horizon police and provide MPC with the high degree of robustness (Besselmann et al., 2016). In comparison with FCS-MPC controller, CCS-MPC requires less time for computing and it has a clear design approach otherwise it is vulnerability to noise and external disturbances effects.

In order to calculate CCS-MPC algorithm, use of online and offline methods are recommended. An online method based on calculations of the control law in each sample interval (Vazquez et al., 2017). The offline mode is based on obtaining explicit control signals with consideration of system operation points and keep these explicit signals. Specification all operating point in which the optimal control moves are determined by evaluating a linear function. Explicit MPC
controllers require lower computation time than the conventional controller. Therefore it is useful for applications which require small sample time (Deshmukh, Aute and Gupta, 2016). Principles of determining suitable operation points are under discussion been in (Besselmann, Lofberg and Morari, 2012), further investigation is beyond the scope of this paper. To implement the CCS–MPC controller, selection of the sample time, the predictive horizon and the control horizon is necessary. The volume of computations depends on the choice of these parameters so that they should be precisely selected until lower processing time needed for the algorithm computations. Some criteria for choosing sample time and prediction horizon are given in (Shridhar and Cooper, 1997) but, in this reference, the first order system with constant time delay is under discussion, while rectifier system model is two order system with one zero. Therefore, this reference method will not provide any appropriate responses in the rectifier system. In this paper, it is suggested that for less sampling time should be selected in each oscillation cycle between 8-12 samples. In this paper, this number is selected 10, and in selecting of the prediction horizon for oscillating systems, it should be noted that the prediction horizon should be able to cover at least one peak or one valley of the wave in order to provide sufficient information about the system model so that the prediction process can be done to produce the control signal properly still, the value of the control horizon should not be taken very high because it diminishes the calculation rate of system.

2.3 Model Predictive Controller Design

In this paper, the primary prediction and control horizon is given the initial value 11 and 2 respectively but the changes in the prediction and control horizon in the system response are still checked. The sample time for the system transfer function discretization according to the system dynamic response is selected 0.00083(s). Sample time is selected 0.00083 (s) and using of zero-pole match method for discretization. The discrete transfer function of the system is given as follow:

\[ h(Z^{-1}) = \frac{0.116Z^{-1} + 0.107Z^{-2}}{1 - 1.858Z^{-1} + 0.8622Z^{-2}} \]  

(21)

Commonly, in GPC technic, controlled autoregressive integrated moving average (CARIMA) model type is used. The equation of CARIMA model can be derived as follows:

\[ A(Z^{-1})y(t) = B(Z^{-1})u(t - 1) + C(Z^{-1})\frac{\xi(t)}{\Delta} \]  

(22)

Where for power electronics and drive application, \( d \) is considered 1, \( \xi(t) \) represent noise in system and \( \Delta = 1 - Z^{-1} \) \( \Delta \) is deviation operator. If \( \xi(t) \) is white noise, \( C(Z^{-1}) \) is set to 1 thus Eq.(22) can be simplified as:

\[ A(Z^{-1})y(t) = B(Z^{-1})u(t - 1) + \frac{\xi(t)}{\Delta} \]  

(23)

In order to calculate the prediction step, the following Diophantine equation is considered as following (Linder et al., 2010):

\[ 1 = E_{j}(Z^{-1})A(Z^{-1})\Delta + Z^{-j}F_{j}(Z^{j}) \]  

(24)

Calculation of \( F \) and \( E \) terms are described in (Linder et al., 2010). The best possible prediction for \( y \) is:

\[ y(t + j) = G_{j}(Z^{-1})\Delta U(t + j - 1) + F_{j}(Z^{-j})y(t) \]  

(25)

In which: \( G_{j} = E_{j}(Z^{-1})B(Z^{-1}) \). In (25) the term of \( G_{j}(Z^{-1})\Delta U(t + j - 1) \) is divide into 2 terms, concerning past and future. Sum of the past output term with \( F_{j}(Z^{j}) \) is named free response (f) and system response to future value is force response. System transfer function \( h(Z^{-1}) \) is expressed as following:

\[ A(Z^{-1})W_{dc}(t) = B(Z^{-1})m_{u}(t - 1) \]  

(26)

At the first step, assuming that there is no constraint in the system, the control signal is obtained by minimizing as follow:

\[ \frac{\partial j}{\partial U} = 2(G^{T}G + \lambda I)U + 2G^{T}(f - w) = 0 \]  

(27)

\[ U = (G^{T}G + \lambda I)^{-1}G^{T}(w - f) \]  

(28)

In MPC controller, receding horizon approach is used and in any optimization one term of control effort (U) is applied to the system (Clarke, Mohtadi and Tuffs, 1987). In the above equation, \( G \) is system dynamic matrix, \( f \) denotes the free
response of the system, \( \lambda \) the weighting factor and \( w \) the reference trajectory.

3. SIMULATION RESULTS

Plotting of the time or frequency response is the first step in any controller design. The rectifier system step response is shown in Fig. 3(a). According to Fig. 3(a), the system output voltage without a controller is not appropriate and has 5% steady state error, as well as the system settling time, is not suitable. Therefore a controller should be designed to improve the system output voltage. Fig. 3(b) depicts the simulation result of the system via the CCS-MPC controller. As can be seen from Fig. 3(b), the use of CCS-MPC controller in the rectifier system has made it possible to provide the fast response with high steady-state precision without having any oscillation or overshoot rectifier output voltage. As a result, the selection of criteria for MPC parameter is acceptable.

The effect of sampling time, prediction and control horizon variation on system performance is discussed in following. Initially, the sampling time will change without altering other parameters. As shown in Fig. 4(a), by increasing the sample time, system dynamic response is also strongly affected and reducing the system speed response. In fact, by increasing the sampling time, a portion of the model is ignored and the signal is not properly recovered and ultimately it reduces system dynamic speed. The effect of reducing the sampling time on the performance of the system has been investigated in Fig. 4(b). The simulation result shown in Fig. 4(b) illustrates the influence on DC side voltage when sampling time is reduced. When the sampling time is set to 0.0002 seconds, the output voltage has a 550V peak in its response, therefore, if sampling time more reduced, it may lead to voltage instability. The system output oscillation reason is related to reduction its sampling time because when the sampling rate is smaller, the little amount of data from the model response is available then the controller cannot be able to generate the optimal signal, that it may even lead to system instability. In other words, in the selection of sampling time, should be established a tradeoff between output response speed, stability, and computational complexity, thus the criterion which is proposed in this paper is an effective solution. The effect of changing the prediction horizon on the system response is investigated in Fig. 4(c). As can be seen from Fig. 4(c), the effect of prediction horizon reduction is approximately equivalent to reducing the sampling time with this difference that decreasing the prediction horizon will reduce the burden of the complexity computations. So, in practice, there will be a relax tradeoff between the system response and facilitates calculation.

Control horizon is another tuning parameter in CCS-MPC controller. In contrast to the two parameters of prediction horizon and sampling time, this parameter has no significant effect on the system stability and it only affects the transient response of the system. The choice of control horizons is important only in constrained systems and its selection is not important for unconstrained systems so that the long control horizon result in more computational volume (Santoyo-Anaya et al., 2018). Fig. 4(d) shows the variation of the control horizon on the system response.

3.1 Analysis of Rectifier Performance with CCS-MPC Controller

In order to show the MPC controller benefits, converter performance when using MPC controller should be investigated. Grid current, PF and THD are very important factors in rectifier converter control, therefore in Fig. 5 is showing these parameters when using the MPC controller. As inferred from Fig. 5, THD and PF parameter in the rectifier system is controlled in the acceptable range, therefore, can be recommended for using this control algorithm in high power rectifier system however in traditional THYRISTOR rectifier, power quality problem is an open topic of research that requires further attention. Following, controller performance has been investigated when the load is increased. Due to the fact, when using the linear model for system behavior representation, this model is valid on system operation point so the system load changes are should be changed around the operation point. In this paper, a modified structure of the MPC controller is used and therefore we expect that this controller can reduce the effect of heavy load change in rectifier performance.

In practical applications, high overvoltage and lower voltage conditions events are very probable. This events causes may be related to starting high load system, the transient overvoltage of capacitors or short circuit fault in the system,
therefore in this conditions the investigation of the rectifier performance is very necessary. Fig. 6(a) shows the rectifier output voltage when a three-phase 30% overvoltage fault has occurred in $t = 0.25$ (s) until $t = 0.4$ (s). As shown in Fig. 6(a), at the fault duration event in the grid, the rectifier output voltage is stabilized. In online CCS-MPC, cost function optimization will be done in any sampling time so the differences between the linear model and real system are decreased as result CCS-MPC controller is robustness again external conditions. This MPC algorithm reduces the uncertain effects of the system on the output voltage and it robust the system in front of severe faults such as over or under voltage.

In the final step, should be tested rectifier performance in harmonic condition. In this case, 20% harmonic order 5 is applied to grid voltage and investigate rectifier performance. As shown in Fig. 6(b), with using MPC controller in rectifier voltage harmonic effects are eliminated in output DC voltage. In practical application, the input voltage of the rectifier converter has some harmonic such as 5 and 7 orders so as a result from Fig. 6(b) using of MPC controller is guaranteed rectifier output voltage in the normal range.

**4. CONCLUSIONS**

In this paper, the linear model of the controllable rectifier is obtained and the specified transfer function is calculated. The main goal of this paper is designing a CCS-MPC controller for regulating rectifier output DC voltage and investigating its performance in the rectifier converter. The criterion for selecting of CCS-MPC sampling time, prediction and control horizon is proposed. This criterion is the specified procedure for tuning the sampling time and prediction horizon with the consideration system dynamic response and the computing power of the processor. Using of CCS-MPC controller demonstrates that it has the appropriate result in some grid and converter characteristics such as grid PF, THD, and output voltage drop value. In particular, when sever changes or faults and disturbances affects the system, MPC controller has the ability to eliminate this outer disturbance.

| Table (1). Rectifier system parameters |
|---------------------------------------|
| Parameter  | Unit | Value  |
| $P_{\text{rectifier}}$  | Kw  | 10    |
| $V_g$       | volt | 180   |
| $V_{\text{dc}}$  | volt | 400   |
| $f_{\text{grid}}$ | Hz  | 60    |
| $L_{\text{grid}}$ | mH  | 1.93  |
| $R_{\text{grid}}$ | Ω   | 0.1   |
| $R_L$       | Ω   | 16    |
| $C$         | μF  | 990   |

Figure 1. Studied rectifier structure.

Figure 2. Rectifier control system.
Figure 3. The Rectifier output voltage step response; without (a) and with (b) CCS-MPC controller with the prediction horizon 11, and the control horizon 2.

Figure 4. The effect of (a) increasing the sampling time, (b) reducing the sampling time, (c) prediction horizon change, (d) control horizon change on the system response.

Figure 5. Grid side current THD and PF with using CCS-MPC controller in Rectifier.
Figure 6. Rectifier Simulation result, (a) output voltage with three phase overvoltage, (b) grid and output voltage in the harmonic condition.

REFERENCES

Besselmann, T. J. et al. (2016) ‘Model predictive control in the multi-megawatt range’, IEEE Transactions on Industrial Electronics. IEEE, 63(7), pp. 4641–4648.

Besselmann, T., Lofberg, J. and Morari, M. (2012) ‘Explicit MPC for LPV systems: Stability and optimality’, IEEE Transactions on Automatic Control. IEEE, 57(9), pp. 2322–2332.

Bordons, C. and Montero, C. (2015) ‘Basic principles of MPC for power converters: Bridging the gap between theory and practice’, IEEE Industrial Electronics Magazine. IEEE, 9(3), pp. 31–43.

Clarke, D. W., Mohtadi, C. and Tuffs, P. S. (1987) ‘Generalized predictive control—Part I. The basic algorithm’, Automatica. Elsevier, 23(2), pp. 137–148.

Dai, L. et al. (2017) ‘Distributed stochastic MPC of linear systems with additive uncertainty and coupled probabilistic constraints’, IEEE Transactions on Automatic Control. IEEE, 62(7), pp. 3474–3481.

Deshmukh, G., Aute, J. and Gupta, A. (2016) ‘Explicit model predictive control for disturbance rejection and tracking control of boost converter’, in 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES). IEEE, pp. 1–5.

Garriga, J. L. and Sorouch, M. (2010) ‘Model predictive control tuning methods: A review’, Industrial & Engineering Chemistry Research. ACS Publications, 49(8), pp. 3505–3515.

Ginn, H. L. et al. (2015) ‘Control Architecture for High Power Electronics Converters’, Proceedings of the IEEE. IEEE, 103(12), pp. 2311–2319.

Hrovat, D. et al. (2012) ‘The development of model predictive control in automotive industry: A survey’, in 2012 IEEE International Conference on Control Applications. IEEE, pp. 295–302.

Huang, A. Q. (2017) ‘Power semiconductor devices for smart grid and renewable energy systems’, Proceedings of the IEEE. IEEE, 105(11), pp. 2019–2047.

Kashif, S. A. R. and Saqib, M. A. (2016) ‘Multiplexed control strategy for a multi-input converter using fuzzy logic algorithm’, Electronics Letters. IET, 52(15), pp. 1327–1329.

Linder, A. et al. (2010) Model-based predictive control of electric drives. Cuvillier.

Lucia, S. et al. (2018) ‘Optimized fpga implementation of model predictive control for embedded systems using high-level synthesis tool’, IEEE transactions on industrial informatics. IEEE, 14(1), pp. 137–145.

Mendez, R., Sbarbaro, D. and Espinoza, J. (2016) ‘High dynamic and static performance FCS-MPC strategy for static power converters’, in 2016 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, pp. 1–7.

Peterson, T. et al. (1992) ‘A nonlinear DMC algorithm and its application to a semibatch polymerization reactor’, Chemical Engineering Science. Elsevier, 47(4), pp. 737–753.

Santoyo-Anaya, M. A. et al. (2018) ‘Current-sensorless VSC-PFC rectifier control with enhance response to dynamic and sag conditions using a single PI loop’, IEEE Transactions on Power Electronics. IEEE, 33(7), pp. 6403–6415.

Shridhar, R. and Cooper, D. J. (1997) ‘A tuning strategy for unconstrained SISO model predictive control’, Industrial & Engineering Chemistry Research. ACS Publications, 36(3), pp. 729–746.

Thomas, J. (2014) ‘Particle swarm optimization based model predictive control for constrained nonlinear systems’, in 2014 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO). IEEE, pp. 397–403.

Vazquez, S. et al. (2017) ‘Model predictive control for power converters and drives: Advances and trends’, IEEE Transactions on Industrial Electronics. IEEE, 64(2), pp. 935–947.
Xiong, L. et al. (2018) ‘Fractional order sliding mode based direct power control of grid-connected DFIG’, IEEE Transactions on Power Systems. IEEE, 33(3), pp. 3087–3096.

Yang, S. et al. (2017) ‘Feedback linearization based current control strategy for modular multilevel converters’, in 2017 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE, pp. 659–665.