

Linear Modelling of Six Pulse Rectifier and Design of Model Predictive Controller with Stability Analysis

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A The AC/DC converter is one of the popular power electronic converters in industrial applications such as in the railway, power supply systems and electric vehicle. In this paper, a three-phase controllable rectifier is considered and its linear model is extracted. Because of MPC controllers benefits, the continuous control set model predictive controller (CCs-MPC) is designed for controlling this rectifier output DC voltage. By considering rectifier dynamic response, the suitable criteria to choose the model predictive controller parameters such as sampling time, prediction horizon and control horizon is proposed. In experimental implantation the computing burden of microcontroller is limit therefore the reaching to optimal and minimum complexity in algorithms implantation is vital problem. In other words by using these proposed criteria for selection of sample time, prediction and control horizon the tradeoff between computational burden, system performance and dynamic stability is made. When using designed MPC controller, the rectifier and grid performance such as total harmonic distribution (THD), power factor (PF) and output voltage ripple have acceptable value. This controller can eliminated the effect of heavy load change on rectifier performance which is very common problem in industrial system. Also, this controller stability guaranteed is checked by using the dual-mode method. The simulation results and controllers performance are validated in MATLAB software

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I. INTRODUCTION

Once Today, power electronic converters have become the most important controllable device in power systems [1]. With using of power electronics converter to merge all of the new energy sources, make possible many advantages such as reduced component counts, weight reduction and control simplicity in power utility and microgrids [2]. In the past, due to the low level of semiconductor manufacturing technology, the converters switching speed was low and making using them impossible or very limit [2]. Nowadays, thanks to semiconductor manufacturing improvements, these

converters can be used in high switching frequency and high power rating, so today, in the power system and industrial application these converters are used at the scale of Gigawatt and with frequency up to 400 kHz [3]. After this progression, they are widely used in microgrids, hybrid/electric transportation vehicles or hybrid energy systems. Benefit of implementation control methods on power electronic converters have been investigated and different methods for control these converters have been proposed in [4]. The conventional Linear controller is used for controlling the output voltage by appropriate tuning the Kp and Ki values, however, this control method have some disadvantage as result researcher tried to develop new control method form past years. Due to the existence of uncertainties and nonlinear behavior in the power electronic system, using the linear

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controller theory is not recommended [5]. So, researchers have tried to use new control methods that solve the linear controller theory problems and use all capacity of this converter. To overcome these problems, new control methods such as neural networks, fuzzy, and sliding mode control as known intelligent control methods has been proposed in [5-6]. The nonlinear controller such as MPC, fuzzy and sliding mode controllers have some benefits and advantage with compression of linear controllers such as dynamic speed, low ripple and ability to consider system model nonlinearity effect and etc. Therefore in recent years especially after microprocessor computational power progression, most of the nonlinear controller are implemented in linear control system. In spite of creating computational burden and being complex in both design and implementation procedures, using these controllers can indeed overcome the disadvantage of ordinary linear controllers but linear controllers nowadays still the first priority in power electronic converters in comparison with this intelligent methods. In recent years theory of the predictive control methods are presented and this control method has gradually been used in the all fields of industrial application. The initial implementation of model predictive control algorithm has been introduced in the chemical and thermal industry [7]. With the advancement of computer processors, the processing speed has been increased dramatically and providing the ability to implement new control method such as model predictive control algorithms in most industrial system [8].

According to the discrete nature of the power electronic converters, the use of predictive control algorithm in these systems has been suggested in [9, 10]. One of the main reasons for using this method in power electronic converters, is the possibility of considering constraints in the controller design. In [11, 12], designing and implementation of constrained model predictive controller methods in power electronic converters have been investigated. The application of predictive control in various types of power electronic converters are reviewed in [13], which has demonstrated the use of this control algorithm in the distributed generation sources become widespread in last years [13].

Generally, model predictive control can be divided into Continuous Control Set (CCS)-MPC and Finite Control Set (FCS)-MPC [14]. In FCS-MPC, searching and selecting the optimal switching mode from among the number of switching states and after applying it to the system, while in the CCS-MPC, the optimal control signal is produced by optimizing the process according to the system dynamic equations. CCS-MPC requires a modulator to generate control signals, which cause the fixed switching frequency, while in FCS-MPC the switching frequency is variable [15]. In [16], these two control methods in the induction motor drive are compared.

In fact, for designing an appropriated controller, modeling the power electronic converters are necessary. In [17, 18], the modeling of these converters and electrical machines drives are discussed. In these references, the Taylor expansion method for small signal modeling without considering large signal modeling and parameter variation is used. Therefore, using small signal model leads to a significant error conditions such as in fault conditions and severe load change, that it may cause disturb control system. The model predictive controller can reduce uncertainties effects on the system performance hence the use of linear models for designing a prediction controller will lead to satisfactory results. But in some literature, such as [19, 20], designing and using of nonlinear model predictive controllers in power electronic converters is proposed, although it contributes to the better performance than linear MPC but leads to complex design and operation aren't suitable for industrial application.

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 [21]. Some of the most important reasons for choosing the appropriate sampling time in the MPC controller are impacts on the calculations time and the dependence of the controller stability. Design and implementation of constrain MPC is another important topic which is discussed in [22, 23]. In most articles that refer to the use of MPC controller in power electronic converters and electrical drives, the issue of choosing an appropriate sampling time and the prediction and control horizon, aren't considered. In most MPC controller applications in power electronics, have not offer analytical method for designing of MPC parameters such as sampling time, prediction horizon and control horizon while in this article, attempt has been made to set these parameters using a dynamic model and system behavior.

In this paper, CCS-MPC for controlling 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, and MPC controller stability proof is investigated by use of the dual-mode method. In the some related works in power electronics, the stability proof is not considered for MPC controller or other new control methods. While in this study, the stability of the proposed controller is investigate and proved. In the VI it is shown that the stability of the MPC controller is related to the prediction horizon and sampling time which indicates the importance of the criterion controller parameters designing procedure.

This paper is arranged as follows. The mathematical and linearized model of the three-phase controllable rectifier is presented in Section 2. Model predictive controller design of rectifier is presented in Section 3. Stability analysis of modified CCS-MPC controller with using dual-mode method

is illustrated in Section 4. The simulation results are describe in Section 5. Conclusions are given in Section 6.

II. MATHEMATICAL MODEL OF THREE-PHASE CONTROLLABLE RECTIFIER

In this section, the three-phase converter (rectifier), which uses the IGBT switches, is investigated. Rectifiers are the oldest and the most used power electronic converters. To use them in high power applications, the input voltage of these converters is usually three phases. To reduce the output voltage fluctuations, a capacitor is usually used as a voltage filter in rectifier structure. Also, a resistive load is used in rectifier structure. The three-phase rectifier topology is shown in Fig. 1.

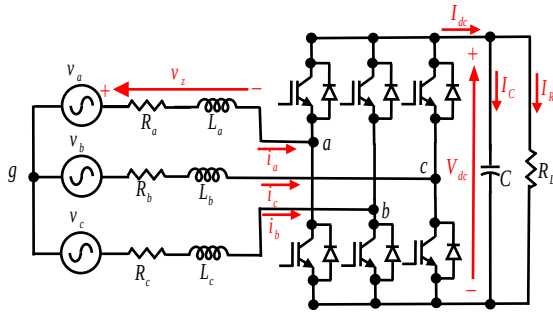


Fig. 1. Studied rectifier structure

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 [25]. With this assumption and with using Table 1 the state equations of the system are given as follows:

$$\frac{di_a(t)}{dt} = -\frac{R}{L}i_a - \frac{1}{L}V_{za}(t) + \frac{1}{L}V_{ga}(t) \quad (1)$$

$$\frac{di_b(t)}{dt} = -\frac{R}{L}i_b - \frac{1}{L}V_{zb}(t) + \frac{1}{L}V_{gb}(t) \quad (2)$$

$$\frac{di_c(t)}{dt} = -\frac{R}{L}i_c - \frac{1}{L}V_{zc}(t) + \frac{1}{L}V_{gc}(t) \quad (3)$$

$$I_{dc}(t) = I_{dca}(t) + I_{dcb}(t) + I_{dcc}(t) \quad (4)$$

$$\frac{dV_{dc}(t)}{dt} = \frac{1}{C}I_{dc}(t) - \frac{1}{CR_L}V_{dc}(t) \quad (5)$$

$$V_{rabc} = \frac{1}{2}m_i(t) * V_{dc} \quad (6)$$

$$V_{rabc} = V_{abc} - V_z \quad (7)$$

$$i_{rabc} = \frac{1}{2}m_i(t) * I_{dc} \quad (8)$$

TABLE.I

PARAMETER DEFINITION OF STUDIED RECTIFIER

Parameter	Definition	Unit
I_{abc}	Grid three phase current	Amp
V_{abc}	Grid three phase voltage	Volt
V_{dc}	Dc link voltage	Volt
C	Capacitor	F
m_i	modulation index	-
I_{dc}	output dc current	-
R	Grid resistance	Ω
L	Grid inductance	H

With sinusoidal grid voltage assumption and using (4) the above equations are rewritten as follows:

$$\frac{di_a(t)}{dt} = -\frac{R}{L}i_a - \frac{m_i}{2L}V_{dc} + \frac{1}{L}V_{ag} \quad (9)$$

$$\frac{di_b(t)}{dt} = -\frac{R}{L}i_b - \frac{m_i}{2L}V_{dc} + \frac{1}{L}V_{bg} \quad (10)$$

$$\frac{di_c(t)}{dt} = -\frac{R}{L}i_c - \frac{m_i}{2L}V_{dc} + \frac{1}{L}V_{cg} \quad (11)$$

$$\frac{dV_{dc}(t)}{dt} = \frac{3m_i}{2C}I_{dc}(t) - \frac{1}{CR_L}V_{dc}(t) \quad (12)$$

$$m_i = 2 \frac{V_{abcg} \sin(\omega t) - V'_{abcg} \sin(\omega t + \varphi)}{V_{dc}} \quad (13)$$

$$\varphi = \tan^{-1} \left(\frac{XL}{R} \right) \quad (14)$$

Where V_{ag}, V_{bg}, V_{cg} are the amplitude of grid voltages and V' is amplitude voltage drop on grid impedance. By using the above equations, the model of the system is written as follows:

$$\frac{di_a(t)}{dt} = -\frac{R}{L}i_a - \frac{1}{L}V_{ra}(t) + \frac{1}{L}V_a(t) \quad (15)$$

$$\frac{di_b(t)}{dt} = -\frac{R}{L}i_b - \frac{1}{L}V_{rb}(t) + \frac{1}{L}V_b(t) \quad (16)$$

$$\frac{di_c(t)}{dt} = -\frac{R}{L}i_c - \frac{1}{L}V_{rc}(t) + \frac{1}{L}V_c(t) \quad (17)$$

$$\begin{aligned} \frac{dV_{dc}(t)}{dt} = & \frac{(i_a + i_b + i_c)}{CV_{dc}} \sqrt{V_g^2 - 2V_g V' \cos(\varphi) + V'^2} \\ & - \frac{1}{CR_L} V_{dc} \end{aligned} \quad (18)$$

TABLE. II
PARAMETER DEFINITION (8-18)

Parameter	Definition	Unit
V_{ag}, V_{bg}, V_{cg}	Grid voltage amplitude	Volt
V'	voltage drop amplitude	Volt
V_{dc}	Dc link voltage	Volt
φ	Power factor	Deg
m_i	modulation index	-
V_g	Phase Voltage	Volt

In (15-18) with considering that grid currents have dependency with together, therefore, one phase current and dc link capacitor voltage are selected as state variables and grid voltages are system input variables respectively. In the state equations, there are some nonlinear term such as $(\frac{I_a+I_b+I_c}{CV_{dc}})$ and $m_i(t)$ therefore for linear analyses, with using 10 kW rectifier parameter (Table I) and using the Taylor expansion method can be linearize of (15-18) around the nominal operation point ($i^{abc} = 26.18, V_{dc} = 400, V' = 19.09$), transfer function is calculated as:

$$H(s) = \frac{V_{dc}}{m_i}(s) = \frac{2.8286(s + 175100)}{(s + 51.17)(s + 125.7)} \quad (19)$$

TABLE III
RECTIFIER SYSTEM PARAMETER VALUES

Parameter	Unit	Value
$P_{rectifier}$	Kw	10
V_g	Volt	180
V_{dc}	volt	400
f_{grid}	Hz	60
L_{grid}	mH	1.93
R_{grid}	Ω	0.1
R_L	Ω	16
C	μF	990

III. MODEL PREDICTIVE CONTROL DESIGN

Because of nonlinear behavior and parameter uncertainties in power electronic converters, by using the new controller, the defects of linear controllers are eliminated [25]. The model

predictive control algorithm is one of the best options for using in power electronic converter applications.

A. Model Predictive Control Algorithm

Model predictive control algorithm generates a proper control signal to stabilize the rectifier voltage. MPC controller is implemented in 4 forms which are: DMC, AMC, PFC, and GPC [26]. In [26], 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 [26], therefore in this paper, it is applied to the rectifier system. The rectifier control system is shown in Fig. 2.

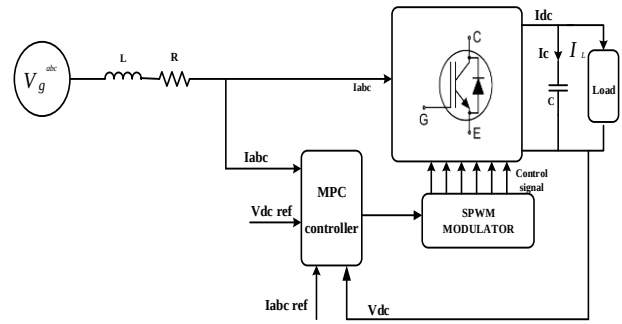


Fig. 2. Rectifier control system.

The MPC is a multivariable control algorithm and the calculation of the optimal control move is based on solving the optimization problem defined by a cost function and the control goal can be prescribed by the quadratic cost function. The MPC controller cost function can be formulated as (20), a control signal can be produced, with minimization of the cost function J:

$$J(N_1, N_p, N_c) = \sum_{j=N_1}^{N_p} \delta(j) [\hat{y}(t+j|t) - w(t+j)]^2 + \sum_{j=1}^{N_c} \lambda(j) [\Delta u(t+j-1)]^2 \quad (19)$$

where, N_p is prediction horizon, N_c control horizon, N_1 model delayed, Δu control signal, $y(t)$ model output(t) reference set point and $\delta(t)$ and $\lambda(t)$ are the weight factors [18].

B. 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 prediction horizon and sample time should be selected according to the system specification [21]. 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 [22, 23].

The MPC controllers are implemented in both schemes of finite control set (FSC-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 [29]. 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 [9]. 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 [10]. 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 [31]. Principles of determining suitable operation points are under discussion been in [32], 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 [33] 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 method will not provide any appropriate

responses in the rectifier system. In this paper, it is suggested that the sampling time should be selected based on model dynamic response and theorem of Shannon which is using in continues model discretization process. Based on digital control theorem, for converting S-domain system to Z- domain model, in each oscillation cycle between 8-12 samples is require until the quantization error is ignorable. 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.

C. 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 in following simulation and investigate this parameters effect on controller response. 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:

$$h(Z^{-1}) = \frac{.116Z^{-1} + .107Z^{-2}}{1 - 1.858Z^{-1} + .8622Z^{-2}} \quad (21)$$

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

$$A(Z^{-1})y(t) = B(Z^{-1})u(t-1) + C(Z^{-1})\frac{\xi(t)}{\Delta} \quad (22)$$

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

$$A(Z^{-1})y(t) = B(Z^{-1})u(t-1) + \frac{\xi(t)}{\Delta} \quad (23)$$

In order to calculate the prediction step, the following Diophantine equation is considered as following [33]:

$$1 = E_j(Z^{-1})A(Z^{-1})\Delta + Z^{-j}F_j(Z^{-1}) \quad (24)$$

Calculation of F and E terms are described in [33]. The best possible prediction for y is:

$$y(t+j) = G_j(Z^{-1})\Delta U(t+j-1) + F_j(Z^{-1})y(t) \quad (25)$$

In which: $G_j(t) = E_j(Z^{-1})B(Z^{-1})$. 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 $F_j(Z^{-1})$ is

named free response (f) and system response to future value is force response. System transfer function $h(Z^{-1})$ is expressed as following:

$$A(Z^{-1})V_{dc}(t) = B(Z^{-1})m_i(t-1) \quad (26)$$

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

$$\frac{\partial J}{\partial U} = 2(G^T G + \lambda I)U + 2G^T(f - w) = 0 \quad (27)$$

$$U = (G^T G + \lambda I)^{-1} G^T(w - f) \quad (28)$$

In MPC controller, receding horizon approach is used and in any optimization one term of control effort (U) is applied to the system [34]. In the above equation, G is system dynamic matrix, f denotes the free response of the system, λ the weighting factor and W the reference trajectory.

IV. STABILITY ANALYSIS OF CCS-MPC CONTROLLER WITH USING DUAL MODE METHOD

To ensure the stability of the controller, it should be demonstrated mathematically. In linear controllers, it is possible to prove the stability through conventional methods, such as an NYQUIST diagram, root locus curve or bode diagram analysis [35]. Stability analysis method of MPC controllers is not as same as linear controllers. In the references such as [36], [37], mathematical methods for proving the stability of MPC controllers have been discussed.

The method examined in this paper is to prove the stability of the MPC controller, known as the Dual Mode method. In (20), if the upper limit of the first summation approach to infinity, the optimization problem is feasible. But in practical and industrial applications, the computation power of microprocessors are limited, therefore, prediction and control horizon are selected on the basis of a specified criteria such as the defined method. Hence MPC controller requires stability investigation. The basis of the Dual Mode method is minimizing the cost function from one until prediction horizon and applying state feedback from the prediction horizon to the infinity. Accordingly, if the conditions of the Dual Mode problem are satisfied, it is strongly claimed that the MPC controller is stable. The rectifier system transfer function in (19) is rewritten as the state space model in below.

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+2) \end{bmatrix} = \begin{bmatrix} 1.83 & -0.83 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} [v_i(k)] \quad (29)$$

$$y(k) = [0.2383 \quad 0.218] \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix}$$

The quadratic cost function with an infinite horizon is written as follows:

$$J = \sum_{j=0}^{\infty} [x^T(k+i)Qx(k+i) + u^T(k+i)Ru(k+i)] \quad (30)$$

As being as, the (30) until infinite prediction horizon is minimized, it will certainly be stable, however in practice the

control horizon is limited, so the (30) is rewritten as following

and this is done by choosing the terminal weighting matrix $\bar{Q}$ so that the term $x^T(k+N_p+1)Q\Delta x(k+N_p+1)$ is equal to the cost over the mode 2, which is equivalent to the state feedback effect [34].

$$J = \sum_{i=0}^{N_p} [x^T(k+i)Qx(k+i) + u^T(k+i)Ru(k+i)] + x^T(k+N_p+1)\bar{Q}x(k+N_p+1) \quad (31)$$

Terminal weighting matrix is achieved by a solution of the LYAPUNOV equation:

$$\bar{Q} - (A+BK)^T Q(A+BK) \geq K^T RK \quad (32)$$

Where A, B are calculated from the state space model and denotes is stated feedback gain.

The LYAPUNOV equation (32) has a unique solution for $\bar{Q}$ if and only if: 1) the eigenvalues of $A+BK$ are located inside in the unit circle, 2) $Q + K^T RK$ where $Q = C^T C$ positive definite [34] is. For the controllable system, by designing an appropriate K , closed-loop poles can be placed at the specified locations [34]. Using terminal weighting matrix, LYAPUNOV

function can be defined as $V(x) = x^T \bar{Q} x$ where $V(x) > 0$ and $\dot{V}(x) < 0$ and ,which guarantee the MPC controller stability.

In summary, this paper suggests dual-mode receding horizon control method with state feedback controller which is applied inside the attractive region and a receding horizon controller applied outside the terminal region [33]. Dual model method concept is shown in Fig. 3.

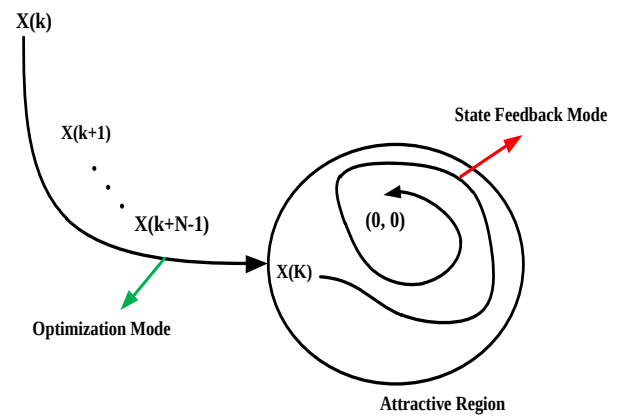


Fig.3. The schematic diagram of the dual-mode method

By using equations of (29) and (32), state feedback gain (K) and terminal weighting matrix ($\bar{Q}$) are defined as follow:

$$K = [1.833, 1.077]$$

$$\bar{Q} = \begin{bmatrix} 5.34 & 1.83 \\ 1.83 & 1 \end{bmatrix} \quad (33)$$

After calculation of $\bar{Q}$ and K , we can claim that designed CCS-MPC controller is stable [38]. In case of power electronic converters and electrical drive applications, stability problem of MPC controller isn't a major issue because their models aren't complex, therefore, using this paper the proposed method for sampling time and prediction horizon selection, don't require for power electronic converters and electrical drive stability evaluate but without using appropriate criteria, stability analysis is needed.

V. 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. 4(a). According to Fig. 4(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. 4(b) depicts the simulation result of the system via the CCS-MPC controller. As can be seen from Fig. 4(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.

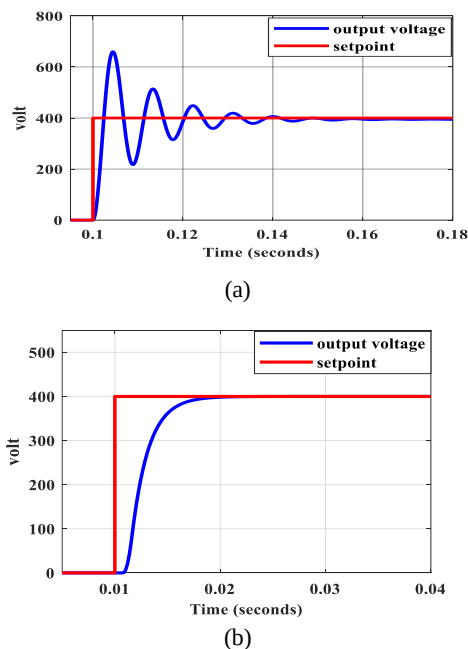


Fig. 4. The Rectifier output voltage step response; without (a) and with (b) CCS-MPC controller with the prediction horizon 11, and the control horizon 2

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. 5(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. 5(b). The simulation result shown in Fig. 5(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. 5(c). As can be seen from Fig. 5(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 [12]. Fig. 5(d) shows the variation of the control horizon on the system response.

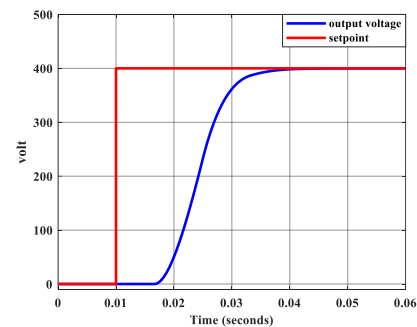


Fig. 5 (a)

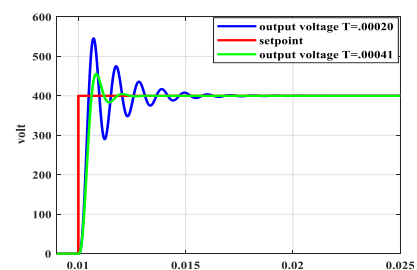


Fig. 5 (b)

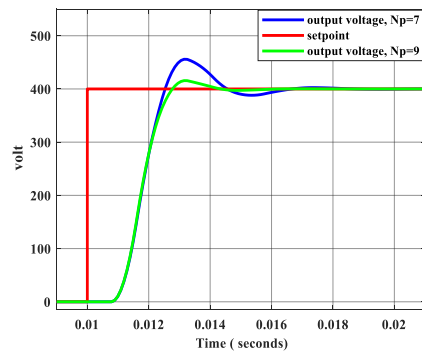


Fig. 5 (c)

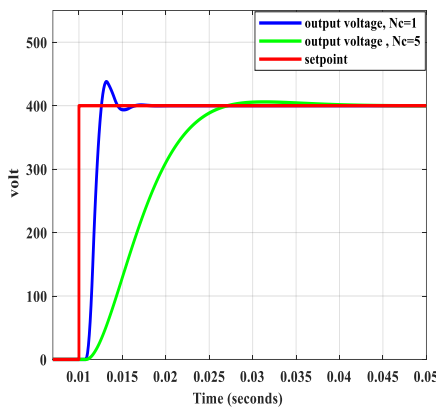


Fig. 5 (d)

Fig. 5. 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.

A. 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. 6 is showing these parameters when using the MPC controller. As inferred from Fig. 6, 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. In output voltage harmonic spectrum is shown that after the main DC component, harmonics in $f=300$ Hz and $f=600$ Hz are other harmonics which is less than IEC61000 3-2 standard values therefore from power quality aspect, this system output voltage is desirable. 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 [28]. 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.

Fig. 8 shows rectifier output DC voltage when the load is increased 20%, 50%, 100% and 150% respectively. As can be noticed, Fig. 8 evidence that when using MPC in the rectifier control system

heavy load variations do not distribute output voltage severely because, in the new structure, nonlinearity of system is reduced by selection of appropriate correction factor. From Fig. 7 can be inferred that when load changes, the rectifier output voltage have steady state error that depends on the value of the new load because when load is increased dramatically, system voltage droop in grid impedance is increased therefore rectifier input voltage is reduced and as a result, this effect cause voltage steady state error in output voltage

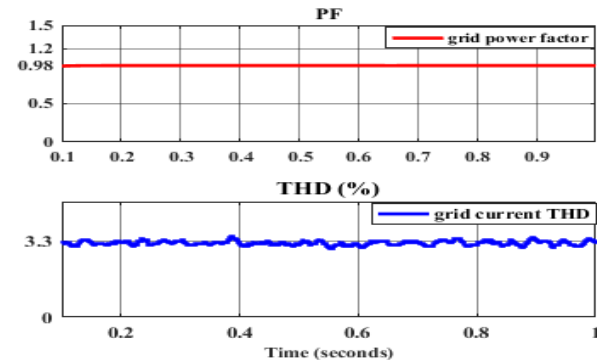


Fig. 6: Grid side current THD and PF when using CCS-MPC controller in Rectifier.

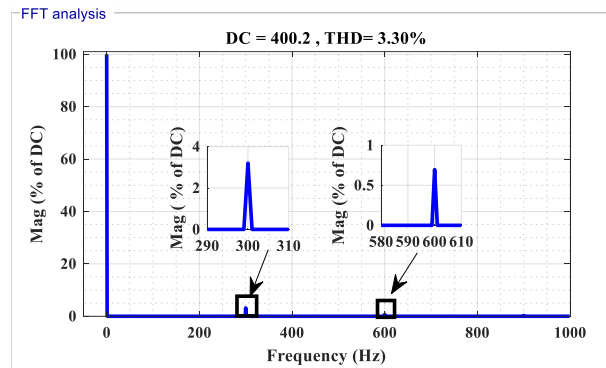


Fig 7: Rectifier output voltage harmonic spectrum

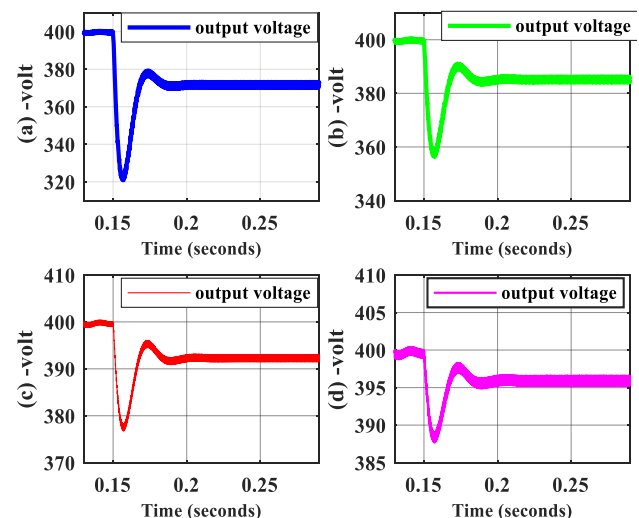


Fig. 8: Rectifier output voltage when load is change in $t = .15$ (s), (a) 150 %, (b) 100 %, (c) 50 %, (d) 25 %.

In practical applications, overvoltage and lower voltage conditions are very probable case. 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. 8(a) shows the rectifier output voltage when a three-phase 30% overvoltage fault has occurred in $t = .25$ (s) until $t = .4$ (s). As shown in Fig. 9(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. 8(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. 8(b) using of MPC controller is guaranteed rectifier output voltage in the normal range.

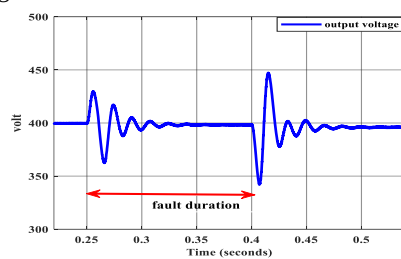


Fig. 9 (a)

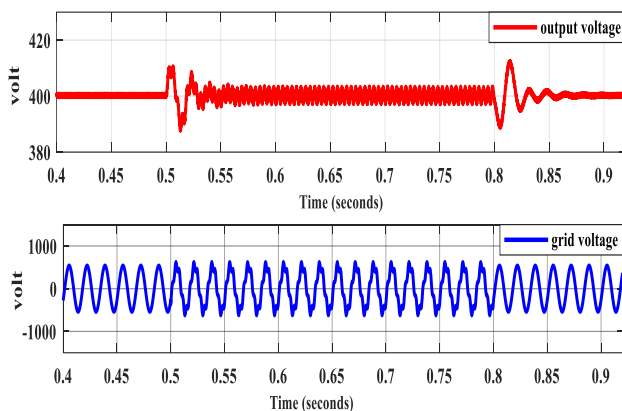


Fig. 9 (b)

Fig. 9: Rectifier output voltage, (a) with three phase overvoltage, (b) in the harmonic condition.

VI. CONCLUSION

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 severe changes or faults and disturbances affects the system, MPC controller has the ability to eliminate this outer disturbance. In this paper, MPC controller stability proof is investigated by using the dual model method. The main result from MPC controller stability procedure, is that, if a valid criterion is used in traditional power electronic converter, the stability analysis won't be a vital problem but if don't regard suitable tuning method in selection of MPC controller parameters, stability analyses and determination of stability margin are vital step in MPC controller design.

REFERENCES

- [1] A. Q. Huang, "Power Semiconductor Devices for Smart Grid and Renewable Energy Systems," in *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2019-2047, Nov. 2017.
- [2] T. J. Besselmann, S. Van de moortel, S. Almér, P. Jörg and H. J. Ferreau, "Model Predictive Control in the Multi-Megawatt Range," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4641-4648, July 2016.
- [3] S. X. She, A. Q. Huang, Ó. Lucía and B. Ozpineci, "Review of Silicon Carbide Power Devices and Their Applications," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 8193-8205, Oct. 2017, doi: 10.1109/TIE.2017.2652401.
- [4] H. L. Ginn, N. Hingorani, J. R. Sullivan and R. Wachal, "Control Architecture for High Power Electronics Converters," in *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2312-2319, Dec. 2015.
- [5] N. u. A. Hanif, S. A. R. Kashif and M. A. Saqib, "Multiplexed control strategy for a multi-input converter using fuzzy logic algorithm," in *Electronics Letters*, vol. 52, no. 15, pp. 1327-1329, 7 21 2016.
- [6] L. Xiong, J. Wang, X. Mi and M. W. Khan, "Fractional Order Sliding Mode Based Direct Power Control of Grid-Connected DFIG," in *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 3087-3096, May 2018.
- [7] S. An overview of industrial model predictive control technology", *Proc. Chemical Process Control-V*, pp. 232-256, 1997
- [8] D. Hrovat, S. Di Cairano, H. E. Tseng and I. V. Kolmanovsky, "The development of Model Predictive Control in automotive industry: A survey," 2012 *IEEE International Conference on Control Applications*, Dubrovnik, 2012, pp. 295-302.
- [9] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo and M. Norambuena, "Model Predictive Control for Power Converters and Drives: Advances and Trends," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 935-947, Feb. 2017.
- [10] C. Bordons and C. Montero, "Basic Principles of MPC for Power Converters: Bridging the Gap Between Theory and

- Practice," in *IEEE Industrial Electronics Magazine*, vol. 9, no. 3, pp. 31-43, Sept. 2015.
- [11] M. Féher, O. Straka, V. Šmídl and Š. Janouš, "Constrained time-optimal control of PMSM with continuous control domain," *2017 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, Pilsen, 2017, pp. 42-47.
- [12] K. G. Pavlou, M. Vasiladiotis and S. N. Manias, "Constrained model predictive control strategy for single-phase switch-mode rectifiers," in *IET Power Electronics*, vol. 5, no. 1, pp. 31-40, January 2012.
- [13] Jose Rodriguez; Patricio Cortes, "Model Predictive Control," in *Predictive Control of Power Converters and Electrical Drives*, 1, Wiley-IEEE Press, 2012, pp.31-39.
- [14] J. Rodriguez et al., "State of the Art of Finite Control Set Model Predictive Control in Power Electronics," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 2, pp. 1003-1016, May 2013.
- [15] P. Karamanakos, T. Geyer, N. Oikonomou, F. D. Kieferndorf and S. Manias, "Direct Model Predictive Control: A Review of Strategies That Achieve Long Prediction Intervals for Power Electronics," in *IEEE Industrial Electronics Magazine*, vol. 8, no. 1, pp. 32-43, March 2014.
- [16] A. A. Ahmed, B. K. Koh and Y. I. Lee, "A Comparison of Finite Control Set and Continuous Control Set Model Predictive Control Schemes for Speed Control of Induction Motors," in *IEEE Transactions on Industrial Informatics*, vol. 14, no. 4, pp. 1334-1346, April 2018.
- [17] A. S. de Moraes, F. Lessa Tofoli and I. Barbi, "Modeling, Digital Control, and Implementation of a Three-Phase Four-Wire Power Converter Used as a Power Redistribution Device," in *IEEE Transactions on Industrial Informatics*, vol. 12, no. 3, pp. 1035-1042, June 2016.
- [18] Seung-Ki Sul, "Basic Structure and Modeling of Electric Machines and Power Converters," in *Control of Electric Machine Drive Systems*, 1, Wiley-IEEE Press, 2011, pp.36-115.
- [19] A.Taheri , N.Asgari "Sliding Mode Control of LLC DCDC Converter for Wide Output Voltage Range in Battery Charging" *International Journal of Industrial Electronics, Control and Optimization (IECO)*, Vol 2, Issue 2, , PP 127-136 spring 2019.
- [20] A. El Kachani, E. M. Chakir, A. A. Laachir, T. Jarou and A. Hadjoudja, "Nonlinear model predictive control applied to a DFIG-based wind turbine with a Shunt APF," *2016 International Renewable and Sustainable Energy Conference (IRSEC)*, Marrakech, 2016, pp. 369-375.
- [21] Mohsen Ehsani¹, Masood Saeidi, Hamid Radmanesh, Adib Abrishamifar " Comparisons between Generalized Predictive Control and Linear Controllers in Multi-Input DC-DC Boost Converter ", *International Journal of Industrial Electronics, Control and Optimization (IECO)*, Vol. 1, No. 3, pp. 27-34, Jan 2020.
- [22] Thomas, "Particle swarm optimization based model predictive control for constrained nonlinear systems," *2014 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO)*, Vienna, Austria, 2014, pp. 397-403.
- [23] L. Dai, Y. Xia, Y. Gao and M. Cannon, "Distributed Stochastic MPC of Linear Systems With Additive Uncertainty and Coupled Probabilistic Constraints," in *IEEE Transactions on Automatic Control*, vol. 62, no. 7, pp. 3474-3481, July 2017.
- [24] M. A. Santoyo Anaya, J. R. Rodriguez-Rodriguez, E. L. Moreno-Goytia, V. Venegas-Rebollar and N. M. Salgado Herrera, "Current-Sensorless VSC-PFC Rectifier Control with enhance response to dynamic and sag conditions using a single PI loop," in *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1-1, Sep 2017
- [25] S. Vazquez et al., "Model Predictive Control: A Review of Its Applications in Power Electronics," in *IEEE Industrial Electronics Magazine*, vol. 8, no. 1, pp. 16-31, March 2014.
- [26] T. Peterson, E. Hernández, Y. Arkun and F. Schork, "A nonlinear DMC algorithm and its application to a semibatch polymerization reactor", *Chemical Engineering Science*, vol. 47, no. 4, pp. 737-753, 1992.
- [27] M. Haeri, "Improved EDMC for the processes with high variations and/or sign changes in steady-state gain", *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering*, vol. 23, no. 2, pp. 361-380, 2004.
- [28] J. C. Basilio and S. R. Matos, "Design of PI and PID controllers with transient performance specification," in *IEEE Transactions on Education*, vol. 45, no. 4, pp. 364-370, Nov 2002.
- [29] R. Mendez, D. Sbarbaro and J. Espinoza, "High dynamic and static performance FCS-MPC strategy for static power converters," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-7.
- [30] G. Deshmukh, J. Aute and A. Gupta, "Explicit model predictive control for disturbance rejection and tracking control of boost converter," *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, 2016, pp. 1-5.
- [31] T. Besselmann, J. Lofberg and M. Morari, "Explicit MPC for LPV Systems: Stability and Optimality," in *IEEE Transactions on Automatic Control*, vol. 57, no. 9, pp. 2322-2332, Sept. 2012.
- [32] R. Shridhar and D. Cooper, "A Tuning Strategy for Unconstrained SISO Model Predictive Control", *Industrial & Engineering Chemistry Research*, vol. 36, no. 3, pp. 729-746, 1997.
- [33] A. Linder, R. Kanchan, R. Kennel, and P. Stolze, "Model-Based Predictive Control of Electric Drives" *Göttingen, Germany: Cuvillier Verlag*, 2010.
- [34] D. Clarke, C. Mohtadi and P. Tuffs, "Generalized predictive control—Part I. The basic algorithm", *Automatica*, vol. 23, no. 2, pp. 137-148, 1987.
- [35] C. Rajhans, S. Patwardhan, and H. Pillai, "Discrete Time Formulation of Quasi Infinite Horizon Nonlinear Model Predictive Control Scheme with Guaranteed Stability", *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 7181-7186, 2017.
- [36] Mayne and J. Rawlings, "Correction to "Constrained model predictive control: stability and optimality"", *Automatica*, vol. 37, no. 3, p. 483, 2001.
- [37] Cannon, Mark Clas lecture Topic" *Model Predictive Control*", C21, department of engineering science University of Oxford, Oxford, 2013.
- [38] I. Zaidi, M. Chaabane, F. Tadeo and A. Benzaouia, "Static State-Feedback Controller and Observer Design for Interval Positive Systems With Time Delay," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 62, no. 5, pp. 506-510, May 2015.



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