

Self-Optimization Systems Design Based on Sliding Mode Control

Dissertation

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Abstract

The objective of control systems is to maintain desired output with the best attainable efficiency, in which such performance of many modern technologies is enhanced via minimizing or maximizing some state variables. Optimization problems are occasionally handled under the condition such that extremum value, local plant gain and required inputs are unknown. Sliding Mode Control (SMC) theory was developed for the plants operate under uncertainty conditions and it exhibits high accuracy, low sensitivity with respect to parameter variations and disturbances. SMC comply with self optimization application requires controlling without gradient evaluation or measurement. This is non-conventional control-system problem, cause gradient takes part of the local gain and it can change sign. In the thesis, searching algorithm is designed with monotonously decreasing or increasing function which is tracked by the output of a plant until the extremum point is reached. Along with developed design principle, aforementioned system behavior in the vicinity of extremum is investigated through deeper analyses, cause the local gain of the plant tends to zero and SMC inherently suffers from the presence of high frequency oscillations, so called chattering. This scope is considered as the theoretical part of the thesis and it is complemented with comparison of other developed methodologies apply gradient vector evaluation. Generalization of the proposed method is demonstrated for multi-dimensional optimization. Beyond theoretical part, three self-optimization problems

are under consideration, which are frequency control of DC/AC inverters implemented on induction motors, output maximization of Underground Coal Gasification (UCG) power plants and capability enhancement of a three-dimensional particle tracking system by integration of an electrically focus-tunable lens.

The objective of minimizing the switching-frequency of DC/AC inverters with desired width of hysteresis results in decreasing heat losses in the power converter. Moreover, decreasing the width of hysteresis loop with remaining the level of admissible frequency will increase the accuracy of inverters.

Gasification of coal deep below the earth surface, known as the Underground Coal Gasification (UCG) process, is very sensitive to the flow rate of oxidants. However, the most critical factor is the steam to oxygen ratio in the input flow rate. Sliding modes based static self-optimization is applied to the UCG process which takes into consideration the inlet pressure of the UCG reactor, adjusts the steam to oxygen ratio such that the reactor output, which is the calorific value of the product gases, is maximized. The simulation results are presented for the validated UCG model to emphasize effectiveness of the algorithm.

SMC self-optimization model is used for tracking an axillary moving microscopic particle of electrically focus tunable lens. Using lenses mounted on mechanical actuators are not efficient against limited movement range, slower response times and vibrations in the system. These drawbacks are often handled by using mathematical models to estimate the state feedbacks before designing the control system. However, the SM the self-optimizing design does not require state feedback information and works by optimizing an output function of the system. The control system is then successfully simulated.



Dedicated to my family ...

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Chapter 1: INTRODUCTION

1.1 Static Self-Optimization Method Based on Sliding Mode Control System

The main stream methods of adaptive control for linear [29], [22], [50] and nonlinear [42] systems are applicable for regulation with known set points or reference trajectories [40]. However, in some applications, such set points are naturally obscure. The optimized, desired output could be obtained by finding the set point in order to overcome existing ambiguity in reference-to-output map. Extremum seeking has been applied widely to engineering systems, including soft landing of electromagnetic actuators [31], PID tuning [33], thermoacoustic coolers [39], antilock braking systems [72], combustion instability [2], and the optimization of variable cam timing engine operations [17], [26], in which those applications have characteristically unreliable and complex nature. Thus, it is important to define optimal operating point in control systems by extremum seeking methods.

Despite a large amount of research efforts expended during the period between the 1940s and 1970s [11], [7], [49], [32], [35], [43], [44], [45], [54], and despite

considerable success in practice [13], [38], [58], the methods of extremum seeking are still in need of further theoretical foundation [37]. The extremum control is first studied by Lablanc (1922) [38], in which it is accepted as first adaptive controller in the literature. Several books in the 1950s-60s have been exclusively or partly dedicated to extremum seeking, including Tsien [62] (1954), Feldbaum [21] (1959), Krasovskii [36] (1963), Wilde [68] (1964), and Chinaev [51] (1969) [30]. On the other hand, Sternbys survey [58] overviews many applications. Extremum seeking search as in Zhang [73], was employed to attenuate combustor thermoacoustic oscillations and minimize diffuser losses at United Technologies Research Center (UTRC); extremum seeking via sliding modes, introduced by Korovin and Utkin [34], and analyzed and applied by Ozguner and co-workers [56], [27] and others [16], [61] on a variety of automotive problems [30].

Optimization is a natural purpose of any control design, that is generally possible with pre-obtained constant set points and sufficient system information which provides necessary adjustments of the outputs in the presence of disturbances. Nonetheless, certain required information are often absent, inaccurate or inadequate. This leads to change in design concepts and proposition of self-optimization systems. A self-optimizing system is able to optimize system's behavior by adapting the structure of utilized mechanical components, controllers, actuators and/or sensors when the system is facing disturbances from the environment and/or by the system itself due to wear or altered user requirements [28].

Consider the simple problem of optimization for a plant, $y = f(x)$, where x and y are input and output signals. The problem of optimization is to provide

maximization or minimization of a system function's output $y = f(x)$ and derivative of the state x is proportional to gradient of that function. Hence derivative of output variable y becomes equal to gradient with some coefficient, γ 1.1. This common approach of optimization might have modifications with using various coefficients, nonetheless the idea is based on gradient of the function and main constraint is obtaining such gradient.

$$y = f(x), \quad \dot{y} = -\gamma f' \quad (1.1)$$

There are many methods introduced to acquire gradient itself or information of it by direct differentiation of input and output, incrementation of one step or probe signals. For instance, probe signals are used in Russian literature [21] called "synchronous detection" illustrated in Figure 1.1

The plant function reaches an extremum at a certain unknown value of x^* and y is assumed to be differentiable. If $y = -\gamma f'$ then $\dot{y} = -\gamma f''$. Then input is assigned as $\sin(\omega t)$ and plant is represented as $f(x) + f'\gamma \sin(\omega t)$. If the output multiplied with $\sin(\omega t)$ and after high frequency components are filtered, we get $f'\gamma$. The average value is $\gamma f'$ and γ determines the convergence rate. Evidently, the output is decaying until the minimum point is reached. It is clear that gradient is needed to implement the control algorithm. It is worth noting that the same idea can be applied for multidimensional optimization, where input x will be k dimensional vector, x_k equals to $\gamma \sin k\omega t$ for k number of inputs. Output of the plant equals to

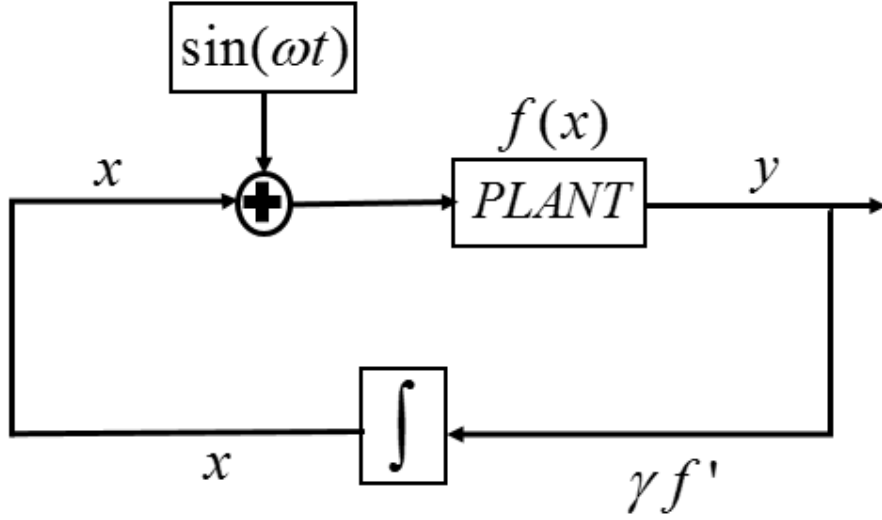


Figure 1.1: Static Self-Optimization Scheme

$$y = f(x) + \frac{\partial f}{\partial x_k} \gamma \sin \omega t \quad (1.2)$$

If y is multiplied with $\sin \omega t$, which gives its average value, it would be proportional to partial derivative with respect to x_k . This system requires k number of probe signals to gather all components of the gradient vector.

Furthermore, sinusoidal perturbation is one of the extremum seeking method used for its fast adaptation feature in [41]. System equation and related control diagram 1.2 are given in the form

$$f(x) = f(x^*) + \frac{f''}{2}(x - x^*)^2 \quad (1.3)$$

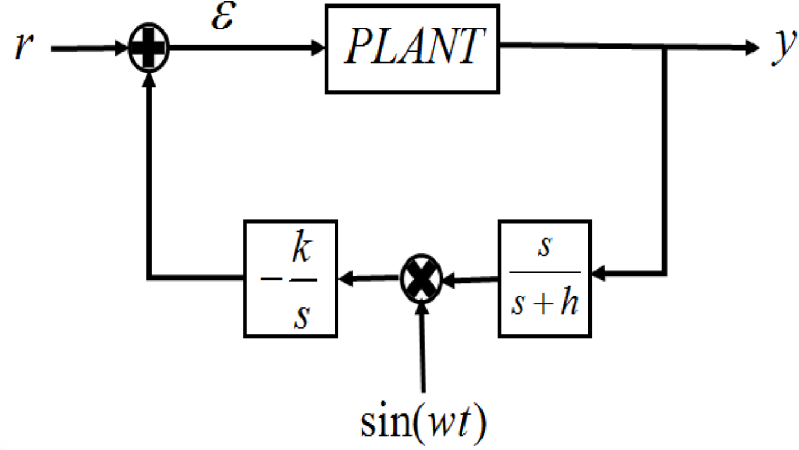


Figure 1.2: Perturbation Model Basic Extremum Seeking Scheme

f'' and k have opposite signs to make difference, $(x - x^*)$, as small as possible to drive plant's output to extremum point. Thus, evaluation of gradient is required beforehand by the designer. However, obtaining information about gradient on mentioned methods require additional implemented components slow down the process and oscillations around the extremum point causes power losses with diluted accuracy. Thus, special methods are developed to get rid of the gradient measurement where SM methodology offers opportune option with designing tracking system.

The purpose of control system is to extract the ultimate performance from the plant with only functioning at its extremum operating point. Static optimization consists in finding a combination of input parameters such that the scalar output of the plant attains an extremal value [63]. The conventional approach to self-optimization is based on calculation or evaluation of gradient. Besides many other

methods, sliding mode control (SMC) also offers solution for self-optimization problems. Sliding Mode Control (SMC) theory is an efficient control-system technique with high accuracy, robustness, low sensitivity to plant parameter variations and disturbances. However, it cannot be used directly, because gradient which takes part of the local gain can change its sign. This makes tracking impossible. In chapter 2 necessary modifications are offered to overcome this problem.

Sliding Mode (SM) self-optimization procedure implies that output tracks monotonously decreasing reference input. As a result, the output value reaches the extremum point. It is shown in the thesis that this approach does not need the gradient function. Sliding mode control approach lets designers implement a tracking system for dynamic plants with sign varying coefficients. Since the local gain is tending to zero when approaching the minimum point, ideal tracking becomes impossible. The conditions for sliding mode existence determines the accuracy of the offered self-optimization procedure. In the previous work [57], in order to preserve the sliding mode, the rate of reference input was gradually decreased, which let the author improve accuracy of the system. In Chapter 2 of the thesis, behavior of the system was analyzed after the sliding mode disappears without any modification of the control algorithm offered in [57].

Convergence to extremum value is achieved but it cannot be utilized directly, because gradient tends to zero and sliding mode disappears while approaching to extremum point. Thus, additional special initial condition is proposed. It is showed that after SM disappears, output of the system keeps on decreasing. In majority of published work, the point where sliding mode disappears was accepted as the measure

of accuracy. If this level is too low, the rate of reference input is decreased, which could slow down the search process. However, it is showed in this thesis that the accuracy neither depends on the rate of reference input, nor depends on conditions of sliding mode existence. It is showed that accuracy determined only by the width of hysteresis loop. This would be the new result. As a result, the higher accuracy of the procedure can be guaranteed.

1.2 Frequency Control of Power Converters

A large part of the worlds electrical energy is converted via power electronic converters which operate with high switching frequency in order to produce desired output in applications. Therefore, the efficiency of power conversion is very important. Typical switching power supplies work with 75-90% efficiency and the energy loss is dissipated as heat whereas such efficiency advances to 95-97% for compact electronic applications. Research has shown that large temperature reduces the life of electronic components, which increases the failure rate of electronics systems [71].

Sliding mode control (SMC) has been studied extensively for over 50 years and widely used in practical applications due to its simplicity and robustness against parameter variations and disturbances [70]. It has low sensitivity to plant parameters and perturbations, which eliminates the exact modeling requirements. It allows to design process system through lower dimensional requirements. All of these makes Sliding Mode Control methodology (SMC) an efficient technique in terms of high dynamic performance, accuracy and convenience of solving very diverse nonlinear control

problems involved with external disturbances and uncertainties. Notwithstanding, it brings along a prominent disadvantage as it accommodates high frequency switching around vicinity of the extremum point, called chattering, created by imperfections of actuators, sensors, switching devices and discrete realizations. This unavoidable phenomena is known as ripples in power area and system is designed such that harmful high frequency components are filtered out by the internal dynamics of the plant. Contrary to former popular belief, it is now understood that working at high switching frequency causes different problems to each specific applications, like heat losses in power converters. Consequently, switching frequency should lie in certain admissible range. Even though, electrical engineers offered some efficient methods in order to suppress ripples with varying hysteresis loop, where these methods are applicable to sliding mode control system, SMC also offered additional methods like state dependent amplitude of control.

The selection an optimal switching frequency of pulse width modulation (PWM) is one of the most effective ways to improve the inverters efficiency [9]. However, the lower switching frequency results in the higher harmonic voltage and current. Thus, the choice of switching frequency is usually considered as a trade-off between lowering the total demand distortion (TDD) of output current and reducing the switching loss [9]. Increasing the carrier signal frequency leads to enhanced dynamic behavior of the control, however, with the side of an augmented thermal stress of the power semiconductors due to the increased switching frequency [60]. Usually, the switching losses and the associated junction temperature rise [20] - [48] characterize the upper limit of the allowable switching frequency of an inverter [60].

Sliding mode is commonly used for hysteresis control, where the width of hysteresis loop determines the accuracy of a system. On the other hand, decreasing the hysteresis loop results in high frequency switching, which causes heat loss. This may lead to unacceptable energy efficiency of the electrical systems. Thus, researchers are interested in finding ways to minimize the frequency with high accuracy or minimizing the width of hysteresis loop and to keep the frequency in the admissible range.

Control of an AC machine should be designed to maintain two variables - torque (speed) and flux at the desired levels. The output of the power converter is three dimensional control and each of them can take 2 values, ± 1 . The control can be designed in correspondence with following methodology: First, two components of current are calculated to provide the desired values of above variables. Then, these currents are tracked by real currents; the third degree of freedom of converter is used to control frequency. Hysteresis control is very popular tool to design current tracking system, but the traditional solutions did not use third degree of freedom [52]. Frequency is the function of neutral voltage at point N and it is selected as the third variable to be controlled.

1.3 Sliding Mode Self-Optimization of Three-dimensional particle tracking system by integration of an electrically focus-tunable lens

Microscope is combination of optic, mechanic or/and electronic instrument assists to observe infinitesimal particles in many scientific areas. Since the first microscope appeared on the stage by its creators Zacharias Jansen and his father, its features and competencies multiplied along with the technological advances. Today, microscopes are treasured with their advanced tracking capabilities besides magnifying capacity. Especially biological phenomenas and particles in fluid mechanisms move into three dimensional observation space, thus special algorithms and control methods are developed for auto-focusing to obtain clear images. It becomes inalienable feature for especially advanced scientific research fields.

Numerous auto-focusing algorithms have been introduced with various distinguishing properties, hence selection of appropriate technique according to each distinct application is extremely important to acquire rewarding results. For instance, in [3] focus algorithms operating on fluorescence images are studied and compared in several applications. Also in [59], eighteen recent focus algorithms are presented and compared in details.

Focus algorithms can be analyzed in four groups [59]

- Derivative-Based

- Statistic-Based
- Histogram-Based
- Intuitive

Categorized algorithms can be compared via using observation methods, like phase contrast, differential interference contrast (DIC) and bright fields. According to [59], normalized variance method provides the best performance in terms of robustness against image noise, pre-processing operation and observation methods. Normalized variance technique is listed under the statistic-based group and it is embraced as a sharpness metric in Chapter 4.

Auto-focusing algorithms are selected based on application and properties of the microscope. In Chapter 4, control design is established regarding a specific microscope equipped with Electrically Tunable Lens (ETL) with Optotune's elastic polymer material and piezo stage which is important for z-direction calibration. Lens is controlled through electrical current changes its curvature for adapting focal point. Thus, ETL should be complemented with appropriate control algorithm. Lateral positions of the particle can be tracked with another control algorithm like centroid method, which is universality accepted robust, fast and accurate technique via using acquired images from camera. However axial position z must be tracked by a separate algorithm.

ETL equipped microscope suffers from deficiency of feedback information required for robust and accurate controlling. Acquired output image is sole possible data to be extracted needed information from. Image is digitalized as excessive length

of matrix where its dimensions correlated with its resolution. Thus, image processing is essential tool to get necessary information for elimination errors caused by non-uniform background noise. Special softwares, like MATLAB, can be used to perform centroid method which is able to implement Moore-Neighbor lateral tracking algorithm modified by Jacob's stopping criteria. Despite satisfying result is obtainable on x and y direction by a preferred method, another control algorithm is required for axial z tracking. Because, lateral positioning becomes void for any movement on z direction which brings image out of observation plane.

In the beginning, z axis tracking was performed by mechanical actuators implemented on microscope lens, however these systems suffer from limited movement range, vibrations and slower response time. ETL does not require mechanical actuators, yet it is required efficient control algorithm to manipulate lens's membrane. Self-optimization sliding mode technique can be used to design a discrete control for an electrically focus tunable lens, such that the focal plane of the lens tracks an axially moving microscopic particle. Camera image is only feedback to be used where mathematical models should be evaluated for state feedback estimation used in control system. Except the advantage of self-optimization sliding mode design optimize output function without state feedback information.

1.4 Underground Coal Gasification System Output Optimization

Coal is one of the oldest energy source of human kind, yet it has been used under its potential. According to World Energy Council (WEC) [10], there is 109 years extractable amount of coal based on 2012 production yield and billions of tons are evaluated as geologically impossible to mine with today's technology. Considering to current conventional mining methods which use only %15 of total potential, the rest awaits future advance in energy technology. Figure 1.3 shows coal demand trajectory from past through its future.

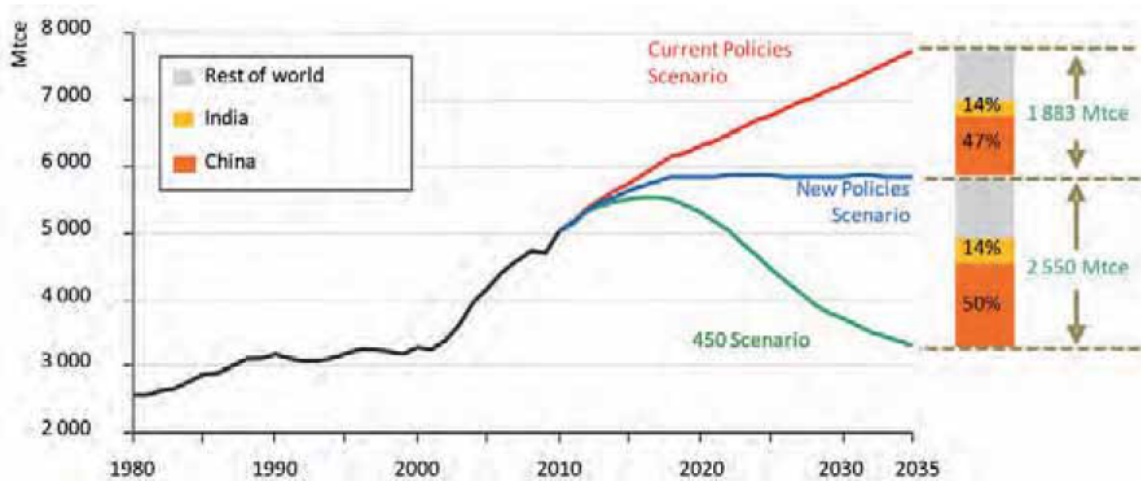


Figure 1.3: World Primary Coal Demand Trajectory

There are two types of coal mining which are underground and opencast mining. Their profit and advantages strictly depend on the geological conditions,

the coal quality and economical feasibility. Underground mining is preferred only where opencast is not an option because underground coal extraction rate is %40 where opencast rate is around %90. Underground mining is limited option because of hazardous gas exhausted due to pressure and temperature related to depth, which becomes impossible to place for workers. Moreover, coal is the most wicked fossil fuel type which exhaust sulfur, mercury, carbon dioxide and other nitrogen derivatives are extremely harmful to ecology. Eventually, major portion of coal is not suitable because of geological impossibility, pure coal quality, environmental reasons and financial unfitness. Coal mining requires great deal of investment, labor force and time, but underground coal gasification (UCG) is great resolution for such concerns.

UCG process is used for low calorific or geologically difficult mines where its carbon emission is far less than conventional coal based thermal power plants. Feasibility tests are essential to obtain coal aging level, compound composition of reserve, properties of earth stratum via three dimensional area identification and hydrogeology modeling. Admissible levels of parameters are explained in Chapter 5. UCG process consists of two underground connected wells, stratum cavity as a reactor and output product processing unit planted on the surface. Meticulously portioned injected gases (steam, oxygen, air) participate series of chemical reactions under the high temperature with pressure, then output gas extracted from production well to be used for further operations. Product gas can be utilized as fuels for power generation and/or also be used for meeting chemical needs like ammonia, methanol, ethanol and other carbon derivatives through Fisher-Tropsch (FTS) process.

UCG process consists of highly nonlinear mathematical models and complex design geometry which makes it very difficult to control under external disturbances and internal model inaccuracies. Since reactions created under the ground with high temperature and pressure, it is impossible to obtain required sensor feedback informations to be used in control model. In [8] UCG process model is introduced and output gas flow is maximized with constant heat level in the frame of sliding mode control method. Results are validated by analytically and also by experiments.

In this research, confirmed UCG process model is used with recommended simplifications to maximize output gas flow by controlling steam-oxygen rate in the frame of self-optimization. Even if desired production level is known and output variable directly depends on control but its function is unknown. Analytical analysis is very difficult due to various high order differential equations and complex nature of UCG process model. Thus, this typical optimization problem is approached with sliding mode control algorithm. Solution requires entire system process, thus related chemical reactions and mathematical model is explained briefly in Chapter 5. Oxygen rate is crucial parameter, where its increase in amount inflates heating value at some point, because char oxidation reaction is exothermic. However increasing oxygen rate causes inflation in carbon dioxide which behaves as extinguisher and decreases heating value and whole UCG process collapses. Thus, maintaining extremum value of unknown oxygen-steam ratio function is required with providing constant heating value.

Chapter 2: CHATTERING ANALYSIS OF SM SELF OPTIMIZATION SYSTEMS

Self-optimization means that input x should be found such that function $y = f(x)$ reaches minimum value. According to the method outlined in the introduction, the tracking system is designed such that $\varepsilon(t)$, the difference between monotonously decreasing the reference input $g(t)$ and the output of the system $y(t)$, is vanished.

$$\varepsilon = g(t) - y(t) \quad \dot{g} = -\rho \quad \dot{x} = u \quad \rho > 0 \quad (2.1)$$

The output tracks the reference input if the sliding mode exists with the condition $\dot{\varepsilon} = -\rho - Af' \text{sign} \varepsilon$ and ε have opposite signs, which is correct for $f' > 0$ and

$$Af' > \rho \quad (2.2)$$

If sign of f' is known, then the sliding mode can be enforced with $u = A \text{sign}(\varepsilon f')$ with sliding mode existence condition stated in 2.2. In [57], a search algorithm was offered such that the sliding mode appears and, as a result, the ideal

tracking is enforced with knowledge of f' . But, in the course of approaching the minimum point, f' tends to zero for differentiable functions and the condition stated in 2.2 is not valid. Thus, this condition cannot serve as a measure of accuracy. The objective of this paper is the analysis of system behavior when the sliding mode disappears and estimation of its accuracy.

However, if f' is unknown, in our system, it will result in positive feedback in one branch of the extremal curve, where the output signal cannot track the reference input $g(t)$. Thus, control should be modified. Since f' is unknown, in order to preserve the SM, the conventional relay function is replaced with discontinuous control with two points of discontinuities.

$$u = A \operatorname{sign}(s_1 s_2) \quad s_1 = \varepsilon \quad s_2 = \varepsilon + \delta \quad (2.3)$$

where δ and A are positive constants. Of course, implementation of this control algorithm implies, as it was mentioned, f' is needed and when approaching the minimum point condition in 2.2 is no longer true. So, we try to modify our control algorithm.

Let the initial conditions be

$$s_1(t)s_2(t) < 0 \quad A \left| \frac{df}{dx} \right| > \rho \quad (2.4)$$

Under the above initial conditions with s_1 or s_2 , the inequality $s_1 \dot{s}_2 < 0$ or $s_2 \dot{s}_1 < 0$ holds. Therefore, s_1 or s_2 will change its sign and so will the derivative of

$\dot{s}_1$ or $\dot{s}_2$; in other words, the inequality $s_1\dot{s}_1 < 0$ or $s_2\dot{s}_2 < 0$ holds in the vicinity of the point $s_1 = 0$ or $s_2 = 0$ [19].

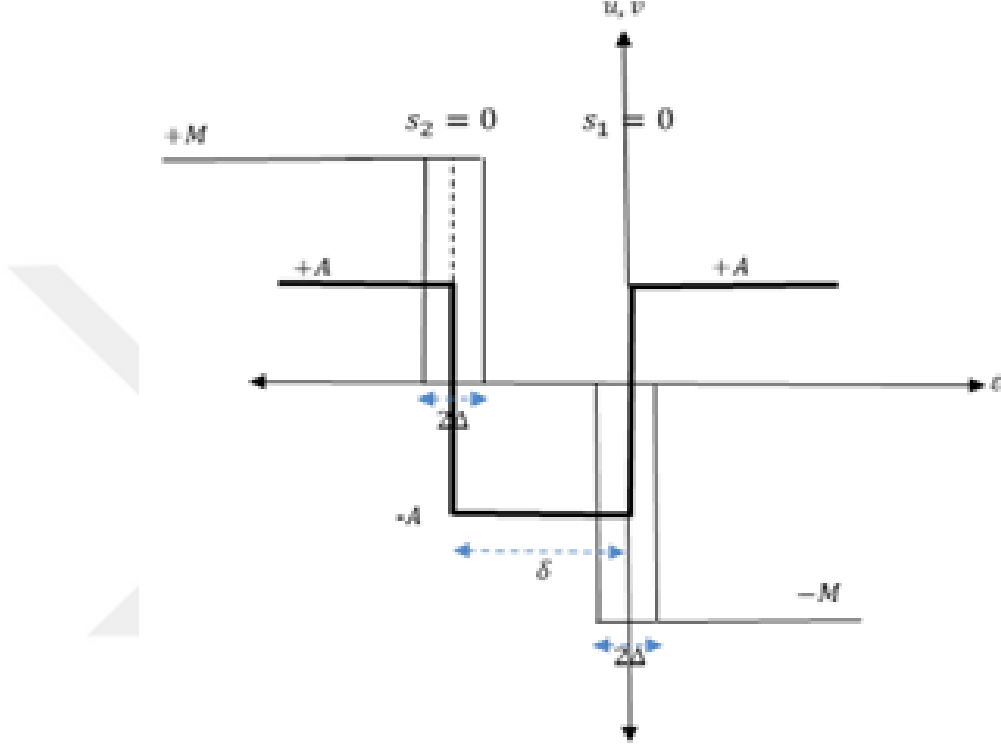


Figure 2.1: Switching Element

From the conditions $\lim_{s \rightarrow +0} \dot{s} < 0$ and $\lim_{s \rightarrow +0} \dot{s} > 0$, it follows that a sliding mode is bound to start in the system and during this motion $s_1 \equiv 0$ or $s_2 \equiv 0$ [63]. Thus, under these initial conditions, sliding mode appears as either s_1 or s_2 and with decaying reference input, sooner or later, the minimum point is reached. When applying this approach, we met two problems, which are f' is unknown and tracking disappears if condition 2.2 is not fulfilled.

In order to create initial conditions 2.4, additional distinct function v with two hysteresis loops is added as shown in 2.1. If function s_1 and s_2 have the same signs for high enough value of M , this function will have opposite signs after a finite time interval; and since by the virtue of equations 2.1, 2.2 and 2.3.

$$\dot{s}_1 = \dot{s}_2 = \dot{\varepsilon} = -\rho + \frac{df}{dx} \text{Asign}(s_1 s_2) \mp v \quad (2.5)$$

In real SM, the function s_1 or s_2 oscillates with small but finite amplitude. The width of hysteresis loop should be greater than this amplitude to avoid activation of function v . Signal v insures the initial conditions described above 2.4 in the system and also makes it possible to stabilize the system motion in the vicinity of the extremum [63]. After extremum vicinity is reached, SM disappears. Thus, v function should be designed large enough and have positive value with $s_1 < 0$, $s_2 < 0$, negative value with $s_1 > 0$, $s_2 > 0$ and be zero with $s_1 s_2 < 0$.

When sliding mode takes place, either one of the sliding functions, s_1 or s_2 , has constant sign and other has variable sign and oscillates at high frequency with low amplitude. When the describing point gets closer to the minimum point, during these variations, $\dot{g}$ is not always equal to $-\rho$ and the set point will not be a monotonously decreasing function anymore. Thus, the switches implementing v function should be designed with hysteresis loops whose width exceeds the double amplitude of oscillations where v is defined as

$$v = \begin{cases} -M & \text{with, } (s_1 - \Delta) > 0 \quad s_2 > 0 \\ 0 & \text{with } (s_1 + \Delta)(s_2 - \Delta) < 0 \\ +M & \text{with } s_1 < 0, (s_2 + \Delta) < 0 \end{cases} \quad (2.6)$$

where 2Δ is width of the hysteresis loop, $M \gg \rho$ and positive constant.

It is evident that if the control is beyond the hysteresis loop, it will be tossed back in the region $(s_1 + \Delta)(s_2 - \Delta) < 0$ and the sliding mode will take the plant output into a certain domain E containing an extremum point and the condition $A \left| \frac{df}{dx} \right| < \rho$. Eventually it is important to note that when the control becomes $s_1(t)s_2(t) < 0$, with condition of $A|f'| > \rho$, sliding mode starts and after some point sliding mode disappears when $A|f'| \leq \rho$. Consequently, no matter whether s_1 or s_2 was zero during motion in sliding mode, the describing point reaches the point $(s_2 - \Delta) = 0$ in further motion; then, according to 2.4, the signal v instantaneously restores the condition $(s_2 = +\Delta)$ and oscillations start as demonstrated showed in 2.2 [63].

The method of solution described here relies on a system which is capable of controlling a plant with sign-varying and unknown gain [63]. Specialty of this system from other wide spread of relay optimization systems are studied comprehensively in [46]. As expected by the virtue of 2.4, even if sliding mode starts on s_1 , control moves to s_2 and average value keeps decaying as illustrated in 2.3. Hence, analysis can only be found in s_2 . However, we cannot assume f' is constant in the vicinity of the minimum point.

SM can be preserved if the rate of function $g(t)$ is gradually decreased. In [57], the existing model is modified and it was shown that the rate of $g(t)$ depends on equivalent control [63].

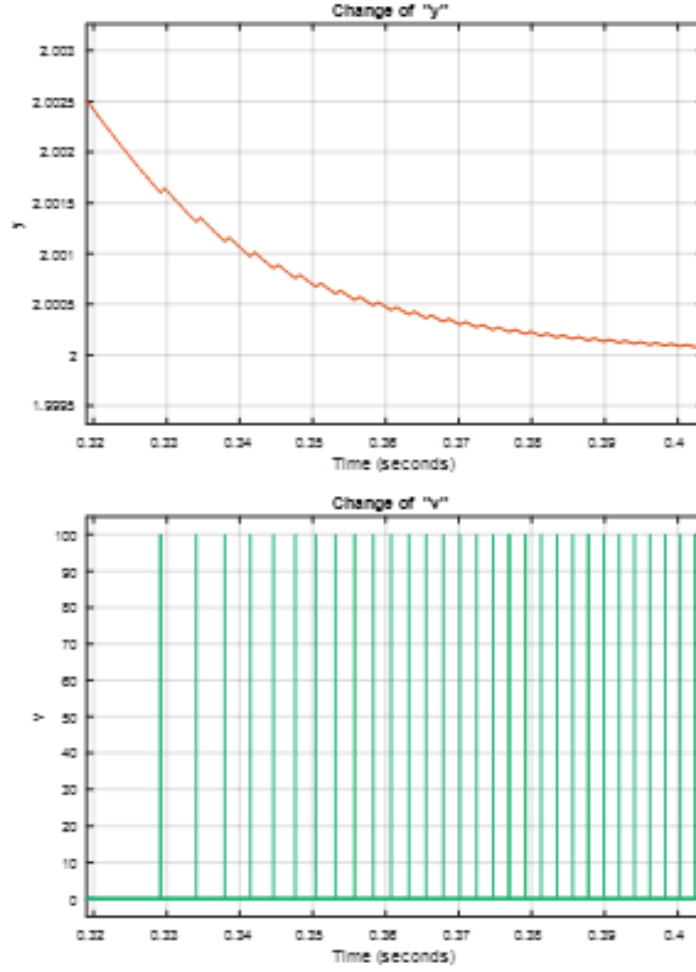


Figure 2.2: Convergence After SM Disappears

$$\rho = -\rho_0 \left(1 - \frac{u}{u_0} \text{sign}(u_{eq}) \right) \quad (2.7a)$$

$$\tau \dot{u}_{eq} + u_{eq} = \frac{u}{u_0} \quad (2.7b)$$

where ρ_0 is a positive constant and u_{eq} is the equivalent control value which can be calculated by a first order filter with sufficiently small time constant τ .

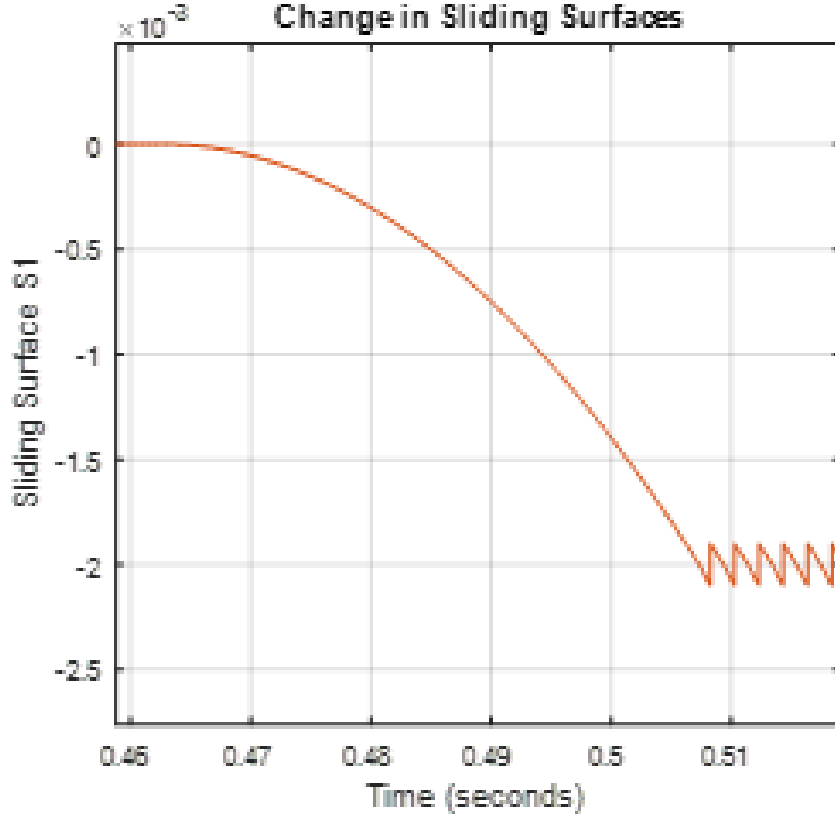


Figure 2.3: Change in Sliding Surfaces

In this system a sliding mode control appears with condition $2\rho_0\tau\ln 2 < \Delta$.

The rate of set-point becomes

$$\rho = -\rho_0 \left(1 - \frac{u_{eq}}{u_0}\right) \quad (2.8)$$

Intuitively it is clear that amplitude of oscillations in the vicinity of the minimum point cannot be less than Δ , since condition 2.4 does not hold and $\dot{s}_1 = \dot{s}_2$ is negative. In this paper, it is shown that both systems accuracy is of order Δ .

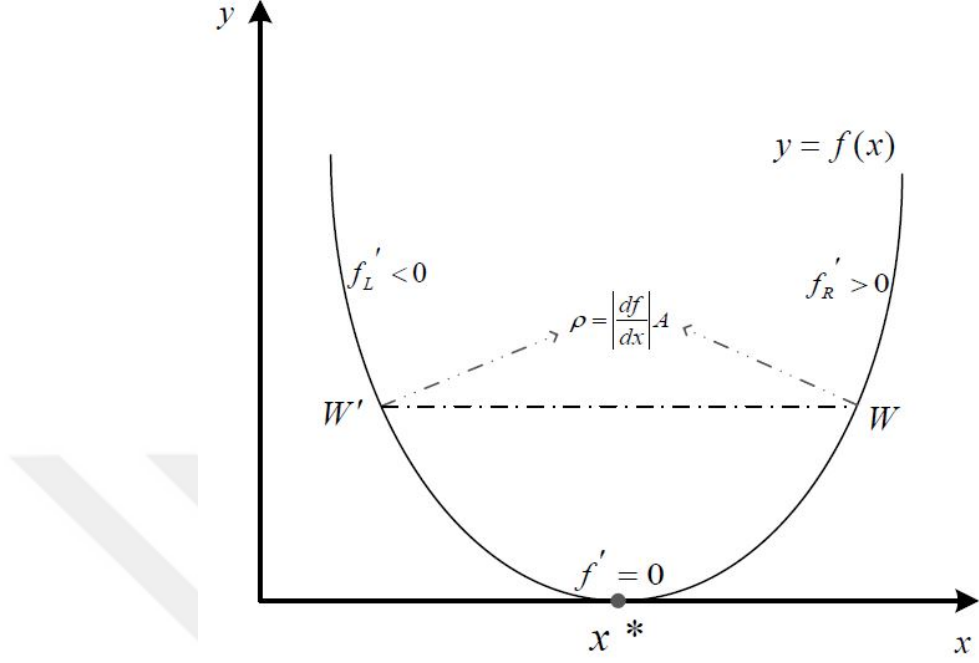


Figure 2.4: Domain without SM

In the modified system, the sliding mode exists in the beginning of the search to the minimum point, but in the unmodified model, it is showed that when sliding mode disappears at point W or W' depicted in above 2.4, the output continues decaying in average to the certain vicinity of extremum. Assuming a small hysteresis width 2Δ and δ , during this short time interval f' could be assumed constant.

2.1 Stability Analysis

Sliding mode disappears when 2.2 is no longer valid, while the describing point reaches some certain vicinity of the extremum point. Since now ρ dominates

the control, it moves toward $(s_2 - \Delta)$ and activates v function. When it is activated, the describing point becomes $(s_2 + \Delta)$ immediately and, contrary to the common belief, it will not move to s_1 , instead, it moves toward back to s_2 , because v function is deactivated. It is shown below by the virtue of 2.4

$$\dot{\varepsilon} = -\rho \mp \frac{df}{dx} A \text{sign}(s_1 s_2) < 0 \quad (2.9)$$

Oscillations repeat until the describing point has reached some vicinity of the extremum point without any sign change of f' . During this motion, the describing point travels $0 \leq s_2 \leq \Delta$ in τ_1 time and output y increases with $f' < 0$ and decreases with $f' > 0$. On the other hand, it travels $-\Delta \leq s_2 \leq 0$ in τ_2 time and output y decreases with $f' < 0$ and increases with $f' > 0$.

$$\Delta = \int_0^{\tau_1} \left(\rho - A \frac{df}{dx} \right) dt \quad \Delta = \int_0^{\tau_2} \left(\rho + A \frac{df}{dx} \right) dt \quad (2.10)$$

Above equation concludes that $\tau_1 < \tau_2$ with $f' < 0$, $\tau_1 > \tau_2$ with $f' > 0$ and oscillation period is $\tau_1 + \tau_2$. By the virtue of 2.4, the plant output change can be calculated as follows

$$\Delta y_1 = \int_0^{\tau_1} \left(A |f'| \right) dt = \Delta - \rho \tau_1 \quad (2.11a)$$

$$\Delta y_2 = \int_0^{\tau_2} \left(A |f'| \right) dt = \Delta - \rho \tau_2 \quad (2.11b)$$

τ_1 and τ_2 can be expressed as follow

$$\tau_1 = \frac{\Delta}{\rho - A \frac{df}{dx}} \quad \tau_2 = \frac{\Delta}{\rho + A \frac{df}{dx}} \quad (2.12)$$

Thus, while the system is in the oscillatory state, when approaching the vicinity of extremum, the mean rate of input change can be estimated as

$$|x_a \dot{v}| = A \frac{Af'}{\rho} < A \quad (2.13)$$

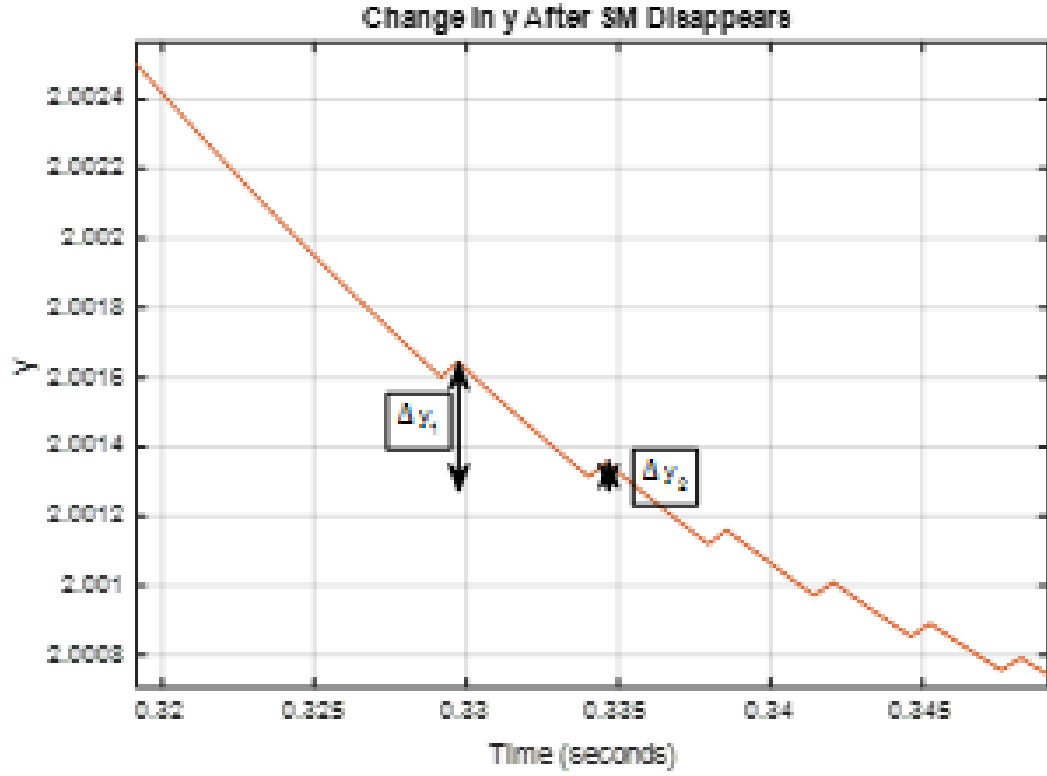


Figure 2.5: Output Change After SM Disappears

In the vicinity of extremum point, we can consider several cases. Let us assume output approaches minimum point when $f' > 0$. The gradient value is f'_R with positive value on the right side of the minimum point, and it is f'_L with the negative value on the left side.

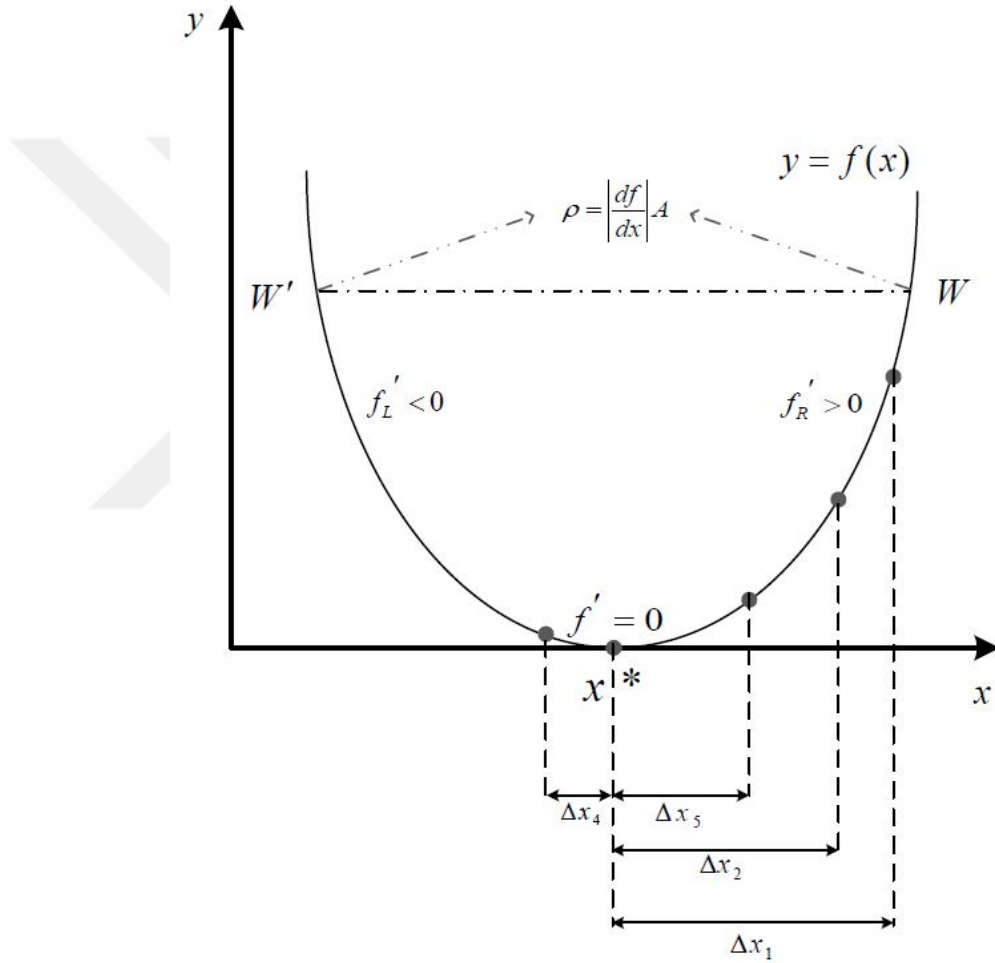


Figure 2.6: Extremum Point Convergence

Consider a point in which control takes place at $+\Delta$. Assume that control reaches $s_2 = 0$ when the minimum point is reached at time τ_1 . Since absolute control speed is $|\dot{\varepsilon}_1| = |\rho - f'_R A|$, τ_1 could be derived and placed in Δx_1 as

$$\Delta x_1 = \frac{\Delta A}{|\rho - f'_R A|} \quad (2.14)$$

Then control reaches $(s_2 - \Delta)$ at time τ_2 with $|\rho + f'_L A|$ absolute speed. Change in x can be derived as above

$$\Delta x_2 = \frac{\Delta A}{|\rho + f'_L A|} \quad (2.15)$$

Since $\Delta x_2 < \Delta x_1$, this proves that input moves toward the extremum. When point $(s_2 - \Delta) = 0$ is reached, v function is immediately activated, so the condition $(s_2 + \Delta) = 0$ holds instantly and one oscillation is completed. Input reaches the minimum point before it reaches $s - 2 = 0$ with $|\rho - f'_R A|$ speed. Assuming input travels distance N at time τ_3 with change in x

$$\Delta x_2 = \Delta x_3 = \frac{NA}{|\rho - f'_R A|} \quad (2.16)$$

When $s_2 = 0$ is reached, the control speed is $|\rho + f'_L A|$ and change of x is increased as

$$\Delta x_4 = \frac{(\Delta - N)A}{|\rho + f'_L A|} \quad (2.17)$$

Since $N < \Delta$, it is evident that $\Delta x_4 < \Delta x_3 = \Delta x_2$. Then input keeps decreasing and finds the minimum point again at distance, C , before reaching $(s_2 - \Delta)$. x takes same distance with slower rate of speed $|\rho - f'_R A|$. When the minimum point is passed, the absolute control speed increases again and with the increased distance of x is calculated as

$$\Delta x_5 = \frac{(\Delta - C)A}{|\rho + f'_L A|} \quad (2.18)$$

Since the minimum point is reached close to $s_2 = 0$ at first with $C < N$, thus, it is safe to say that $\Delta x_5 > \Delta x_4$. Additionally, since $\Delta > N$, it is evident that $\Delta x_5 < \Delta x_2$.

Consequently, after sliding mode disappears, the average value of output continues decaying. In the area of the extremum point, the difference between minimum value of minimized function and real output is of Δ order. So, Δ is measure of search process.

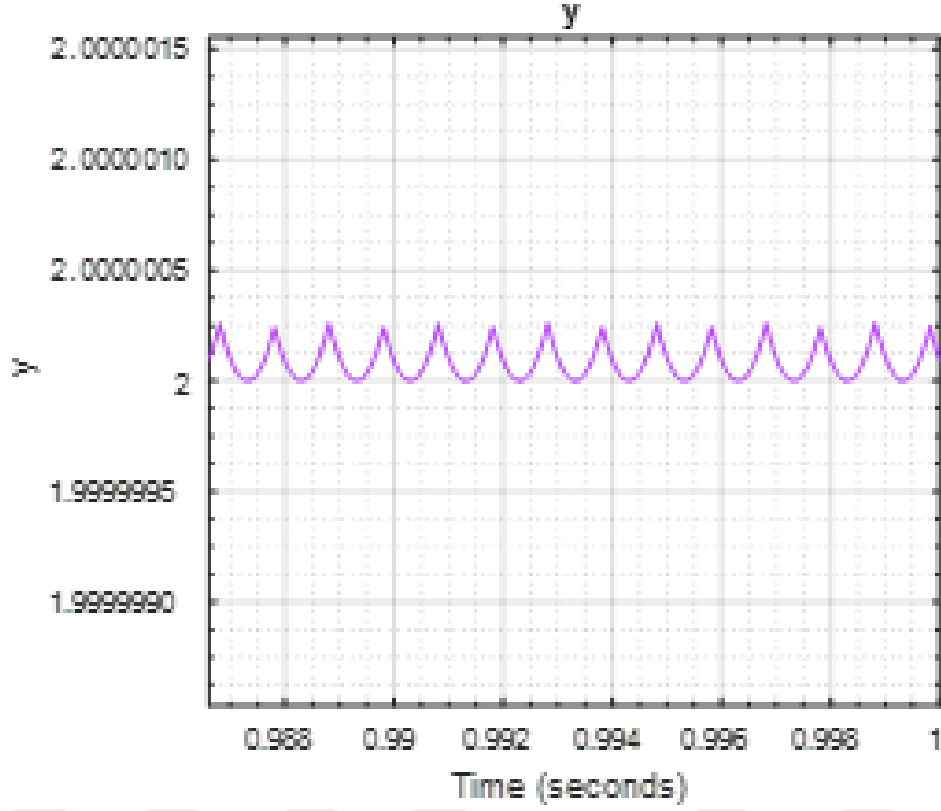


Figure 2.7: Chattering Amplitude

2.2 Comparison with Time Varying Search Speed

In this chapter, two used methods are compared in case of time varying search speeds. In the unmodified method, control is not constrained. Thus, the rate of convergence of these two models differ from each other.

The equivalent control for the modified model is designed as follows

$$u_e q = \frac{\rho_0}{\rho_0 + u_0 |f'|} u_0 \quad (2.19)$$

In the equivalent control method, v function will not be activated after SM appears, because sliding mode does not disappear and the convergence rate of modified model's output can be written as follows

$$|g_a \dot{v}| = |y_a \dot{v}| = \rho_0 \left(1 - \frac{\rho_0}{\rho_0 + u_0 |f'|}\right) \quad (2.20)$$

On the other hand, the unmodified model's convergence rate can be calculated in the stability analysis chapter as

$$|y_a \dot{v}| = \frac{A^2 f'^2}{\rho_0} \quad (2.21)$$

Comparison of search speed of these two methods is as follows

$$\left[\frac{A^2 f'^2}{\rho_0} \right] \quad \text{versus} \quad \left[\rho_0 \left(1 - \frac{\rho_0}{\rho_0 + u_0 |f'|}\right) \right] \quad (2.22)$$

$$\text{If } Q = \frac{A f'}{\rho_0} \quad \text{then } Q \quad \text{versus} \quad \frac{1}{1 + Q} \quad (2.23)$$

If we take $B = A f'$, which has root at $B \simeq 0.62 \rho_0$. It proves that as time goes to infinity, $|f'|$ approaches to zero, and with taking derivative of the convergence rate we see that conventional model reaches zero but equivalent control method reaches

constant value A . Hence, even if the conventional method is faster than the equivalent model at the beginning of the search, at some point close to the extremum point equivalent model becomes faster.



Chapter 3: FREQUENCY CONTROL PROBLEM

3.1 Model and Problem Statement

The DC/AC inverters are commonly used for controlling three phase loads like AC motors, un-interruptible power supply (UPS), balance of systems (BOS). Output currents of an inverter are used to control the flux and torque of AC motors. Pulse width modulation (PWM) techniques are usually used for inverters to control AC motors. Commonly used PWM techniques like, Space vector PWM [25], sine-triangle PWM [47], hybrid PWM [12] and other types of PWM control technologies provide different efficiencies in terms of robustness against disturbances, harmonics loss, tracking ability. Sliding mode control is another technique, which is used via tracking proper reference inputs [64]. Sliding mode control (SMC) is very natural preference for power converter control [65], since the switching between two discrete values can be used directly as gating signals to the semiconductor switching devices in power converter circuits [67].

In sliding mode self-optimization procedure, the width of hysteresis loop determines the accuracy of a system where decreasing the hysteresis loop results in high frequency switching that causes heat loss. This may lead to unacceptable energy efficiency of the electrical systems. Thus, researchers are interested in finding ways to minimize the frequency with high accuracy or minimizing the width of hysteresis loop and to keep the frequency in admissible range.

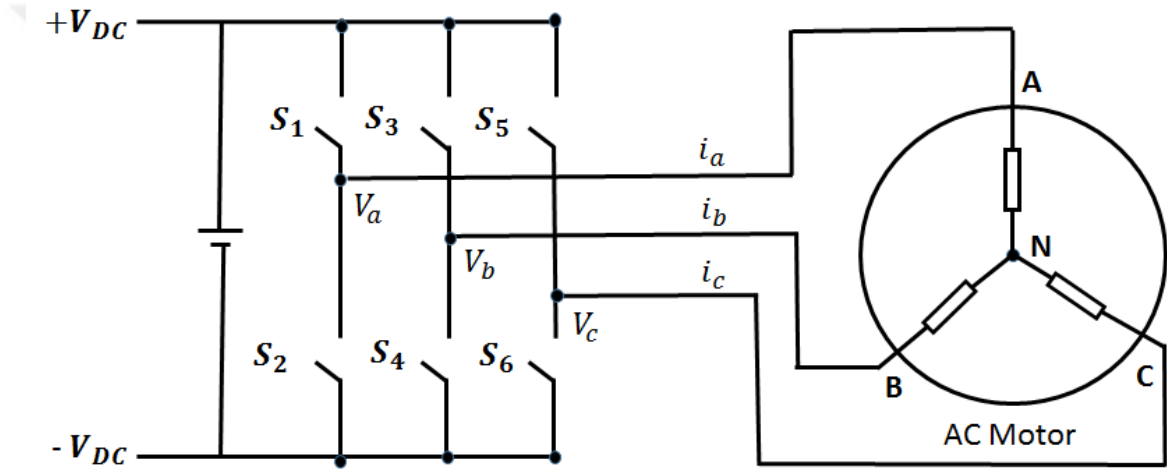


Figure 3.1: Circuit Diagram of Three Phase Inverter and Load

Control of an AC machine can be designed through torque or speed and flux at its desired levels. Figure 3.1 illustrates the circuit diagram of three phase inverter implemented on induction motor. Power converter output control is three dimensional where switch can take 2 values, ± 1 . Thus, corresponding discontinuities can be utilized by sliding mode properties. In this study, two phase currents track preset desired reference and the third degree of freedom is used to control frequency.

Note that, despite current tracking is very popular in hysteresis control, third degree of freedom has not been used for control. Frequency is picked as a function of neutral voltage at point N and it is selected as the third variable to be controlled.

Assume that the ideal three phase full bridge inverter controls an induction motor and system is governed by the equations

$$L\dot{i}_a + Ri_a + E_a = H_1V_{dc} - V_N \quad (3.1a)$$

$$L\dot{i}_b + Ri_b + E_b = H_3V_{dc} - V_N \quad (3.1b)$$

$$L\dot{i}_c + Ri_c + E_c = H_5V_{dc} - V_N \quad (3.1c)$$

where , H_1 , H_3 and H_5 are the switching functions for six switches, $S_{1..6}$, of the full bridge inverter. E_a , E_b , E_c are the back EMF voltage generated by the load and ideally the sum of them are equal to zero. V_N is the neutral point voltage and it can be calculated as

$$V_N = \frac{V_{dc}}{3}(H_1 + H_3 + H_5) \quad (3.2)$$

Equation 3.1 can be redefined with the virtue of Kirchhoff's law

$$\dot{i}_a = K_a + \frac{V_{dc}}{3L}(2H_1 - H_3 - H_5) \quad (3.3a)$$

$$\dot{i}_b = K_b + \frac{V_{dc}}{3L}(2H_3 - H_1 - H_5) \quad (3.3b)$$

$$\dot{i}_c = K_c + \frac{V_{dc}}{3L}(2H_5 - H_3 - H_1) \quad (3.3c)$$

$K_{3 \times 1}$ vector is presented as

$$Ka = -(R/L)i_a - E_a/L \quad (3.4a)$$

$$Kb = -(R/L)i_b - E_b/L \quad (3.4b)$$

$$Kc = -(R/L)i_c - E_c/L \quad (3.4c)$$

$$(3.4d)$$

The torque and speed of the AC machines are the two variables to be controlled. From the equations with respect to torque and flux, the desired currents can be calculated. The control system should be designed to track these functions by real currents. The dependence between the frequency and the voltage of neutral point V_N will be found. The control system should find the value of V_N such that the sum of three switching frequencies in the shoulders of the power converter are minimized. As a result, heat losses in the converter will be minimized as well.

3.2 Sliding Mode Control Algorithm

The three phase inverter generates three dimensional control. Correspondingly, variables under the control are two phase currents and with reference inputs, i_a^* , i_b^* and i_c^* the neutral point voltage with the reference input V_N^* . As follows from the equation 3.2, V_N discontinue function. Because of that, the objective of the control is to make the average value of V_N to be equal to V_N^* . Three sliding mode surfaces are introduced for each degree of freedom.

$$s_a = i_a^* - i_a \quad (3.5a)$$

$$s_b = i_b^* - i_b \quad (3.5b)$$

$$S_V = \int (V_N^* - V_N) d\tau \quad (3.5c)$$

Generally speaking, the differential equations for s_a , s_b and s_V are interconnected with respect to control. It is reasonable to define a new set of three sliding surfaces in order to decouple the design procedure [66].

$$\bar{s} = \frac{1}{3L} \begin{bmatrix} Ls_a + s_V \\ Ls_b + s_V \\ -L(s_a + s_b) + s_V \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \quad (3.6)$$

Then, the differential equations with respect to any component of vector $\bar{s}$ depends on only one component of the control and V_N^* . To get these equations, we should differentiate the equation 3.6

$$\dot{\bar{s}} = a - \frac{V_{dc}}{3L} \begin{bmatrix} H_1 \\ H_3 \\ H_5 \end{bmatrix} \quad (3.7)$$

where $a_{3 \times 1}$ is a vector, which does not depend on any control variables H_1 , H_3 and H_5

$a_{3 \times 1}$ is derived from equation 3.6 and written below

$$a_1 = \underbrace{\frac{1}{3}i_a^* - \frac{1}{3}K_a}_{g_1} + \frac{1}{3}V_N^* \quad (3.8a)$$

$$a_2 = \underbrace{\frac{1}{3}i_b^* - \frac{1}{3}K_b}_{g_2} + \frac{1}{3}V_N^* \quad (3.8b)$$

$$a_3 = \underbrace{-\frac{1}{3}(i_a^* + i_b^*) + \frac{1}{3}(K_a + K_b)}_{g_3} + \frac{1}{3}V_N^* \quad (3.8c)$$

Three phase inverter switches are triggered by

$$H_1 = \text{sign}(\bar{s}_1) \quad (3.9a)$$

$$H_3 = \text{sign}(\bar{s}_2) \quad (3.9b)$$

$$H_5 = \text{sign}(\bar{s}_3) \quad (3.9c)$$

If $V_{dc}/3L$, then the time derivative of each component of vector $\bar{s}$ has the sign of opposite to this component. It means that manifold $\bar{s}$ equal to zero, is reached after finite time, and after that sliding mode occurs in this manifold.

We assume that the control is implemented by the switching devices hysteresis. The width of the hysteresis loop is Δ . In order to calculate the frequency, first, the time interval $t_{ONi}(V_N)$ is found such that H_i is equal to 1. Then, the time interval $t_{OFFi}(V_N)$ is calculated such that H_i is equal to -1. It can be easily done, because we deal with three independent equations of the first order:

$$t_{ONi}(V_N) = \frac{\Delta}{\left| \frac{V_{dc}}{3L} - a_i(V_N^*) \right|} \quad (3.10a)$$

$$t_{OFFi}(V_N) = \frac{\Delta}{\left| \frac{V_{dc}}{3L} + a_i(V_N^*) \right|} \quad (3.10b)$$

Finally, the switching frequency can be found as

$$f_{switching_i} = \frac{1}{t_{ONi} + t_{OFFi}(V_N)} \quad (3.11)$$

As follows to equations 3.9 and 3.10,

$$f_i = \frac{3L}{2\Delta V_{dc}} \left[\left(\frac{V_{dc}}{3L} \right) - a_i^2 \right] \quad (3.12)$$

where $|a_i| < V_{dc}/3L$. Total switching frequency is

$$f_{switching}(V_N) = \sum_{i=1}^3 f_{switching_i}(V_N) \quad (3.13)$$

Sum of the switching frequency is calculated as

$$f_{\Sigma} = \frac{3L}{2\Delta V_{dc}} \left[3 \left(\frac{V_{dc}}{3L} \right)^2 - a_1^2 - a_2^2 - a_3^2 \right] \quad (3.14)$$

In our case, $a_i = g_i + \alpha V_N^*$ with $\sum g_i = 0$, $\alpha = 1/3L$. It means that f_{Σ} can be written as

$$\begin{aligned}
f_{\Sigma} &= \frac{3L}{2\Delta V_{dc}} \left[3 \left(\frac{V_{dc}}{3L} \right)^2 - \sum_{i=1}^3 (g_i + \alpha V_N^*)^2 \right] \\
&= \frac{3L}{2\Delta V_{dc}} \left[3 \left(\frac{V_{dc}}{3L} \right)^2 - \sum_{i=1}^3 (g_i)^2 - 3\alpha^2 (V_N^*)^2 \right]
\end{aligned} \tag{3.15a}$$

The equation 3.16 shows that the equation 3.14 can be drawn as in 3.2. If we take the derivative of the equation 3.14

$$\frac{\partial f_{\Sigma}}{\partial V_N^*} = \frac{1}{\Delta V_{dc} L} V_N^* \tag{3.16}$$

which means that f_{Σ} is the maximum value when $V_N^* = 0$. Our objective is minimization of f_{Σ} by proper choice of $V_N^* = 0$, of course preserving the sliding mode existence $V_{dc}/3L > |a_i|$, $i = 1, 2, 3$. Therefore, if we select a proper value of $V_N^* = 0$, inverter can operate at low switching frequency with the same efficiency. Hence, the efficiency of the inverter can be increased relatively.

$$f_{\Sigma} \longrightarrow |V_N^*| = (V_N^*)_{max} \tag{3.17}$$

As follows from the equation 3.8, in order to select a_i , the points g_i should be shifted up or down by the value of V_N^* and a_i should be between $V_{dc}/3L$ and $-V_{dc}/3L$. Suppose that at some time instance g_1 , g_2 and g_3 are located as shown in 3.3, such that.

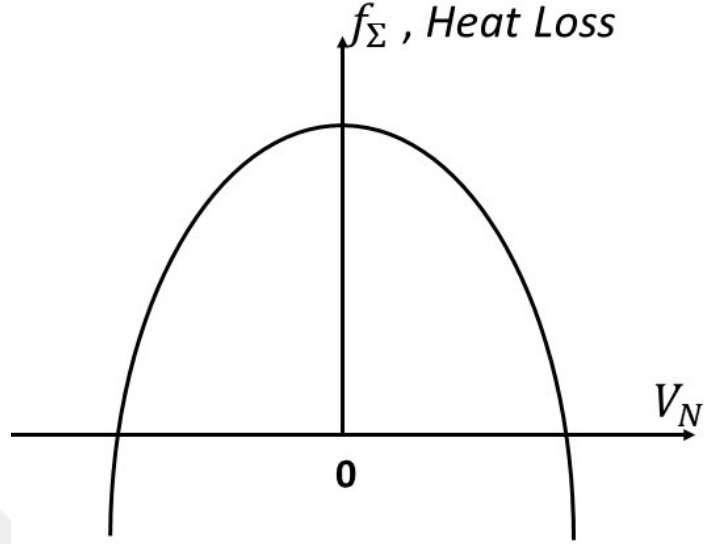


Figure 3.2: Dependence of Heat Losses with Neutral Voltage

The points a_1 , a_2 and a_3 can be obtained by shifting points g_1 , g_2 and g_3 up or down by value of V_N^* . Maximum value of should be found such that all three points a_1 , a_2 and a_3 are between $V_{dc}/3L$ and $-V_{dc}/3L$. It is evident from 3.3, that the maximum value can be found from equation

$$V_N^* = \left[\frac{V_{dc}}{3L} - |g_3| \right] \text{sign}(g_3) \quad (3.18)$$

In general cases, $|g_i| > |g_j| > |g_k|$ with i, j, k can take any combination of 1, 2, 3.

$$V_N^* = \left[\frac{V_{dc}}{3L} - |g_j| \right] \text{sign}(g_j) \quad (3.19)$$

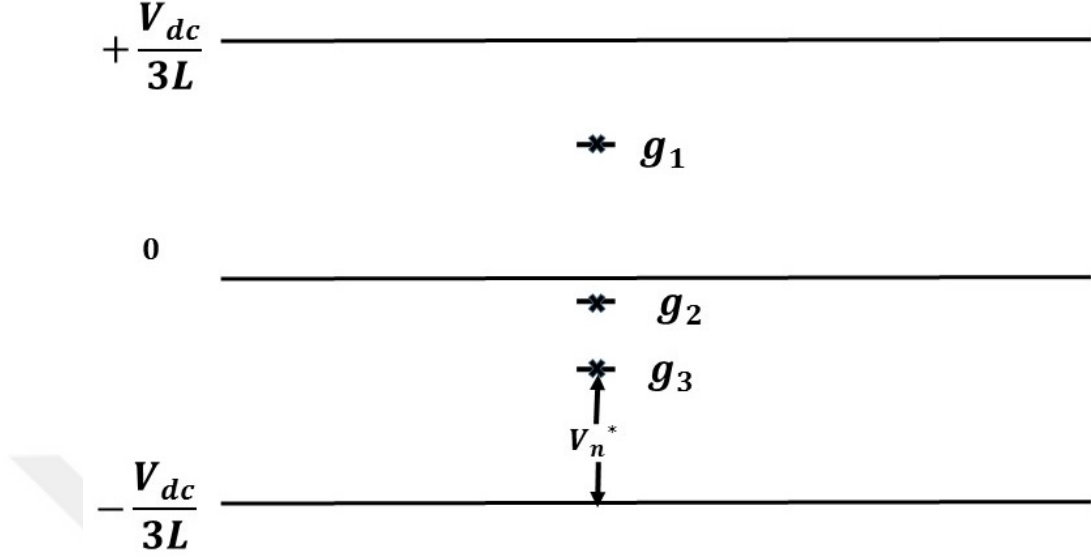


Figure 3.3: Calculation of Reference Neutral Voltage

g_1 , g_2 and g_3 are time functions, because of that the reference inputs for V_N^* in switching function s_V should be a time function too.

It will be demonstrated how the developed methodology can be used to improve the accuracy of the system for the case such that the maximum admissible frequency is given. It can be done for the case, when $g_1 > 0$ and negative numbers g_2 and g_3 are equal, as shown in Figure 4. As follows from equation 3.4, the switching frequency corresponding to g_1 is lower than those for g_2 and g_3 .

If we add negative V_N^* , we will increase the frequency at g_1 and decrease the frequency at g_2 & g_3 until they become equal to each other. As a result, we will have equal frequencies at all three points which are lower than the admissible frequency. It means that we can decrease the hysteresis loop and improve the accuracy

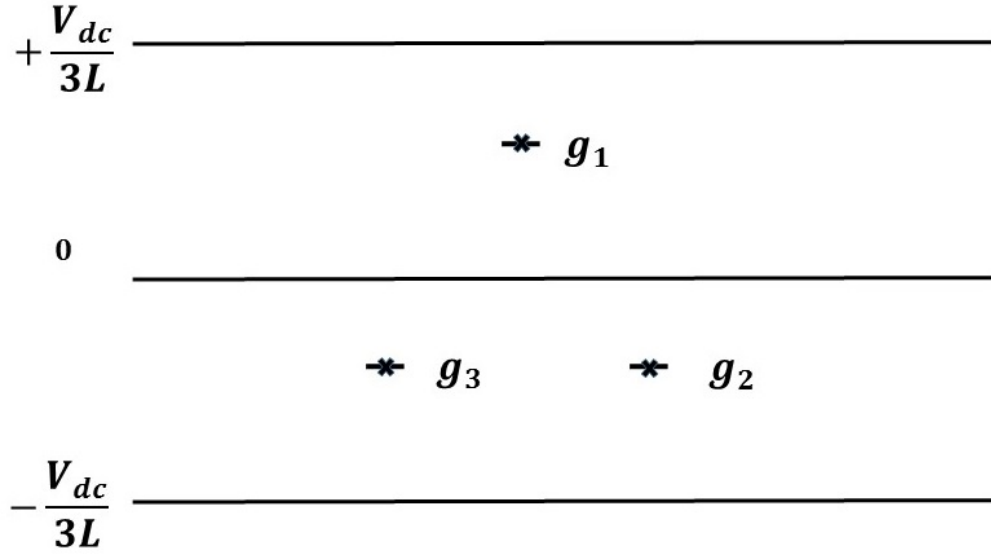


Figure 3.4: Controlling Maximum Switching Frequency

3.3 Simulation Results

The system is modeled by using Matlab/Simulink software. The first set of simulation is related to control of the induction motor. It means that real currents should track the reference ones and the average value of V_N should track reference input V_N^* .

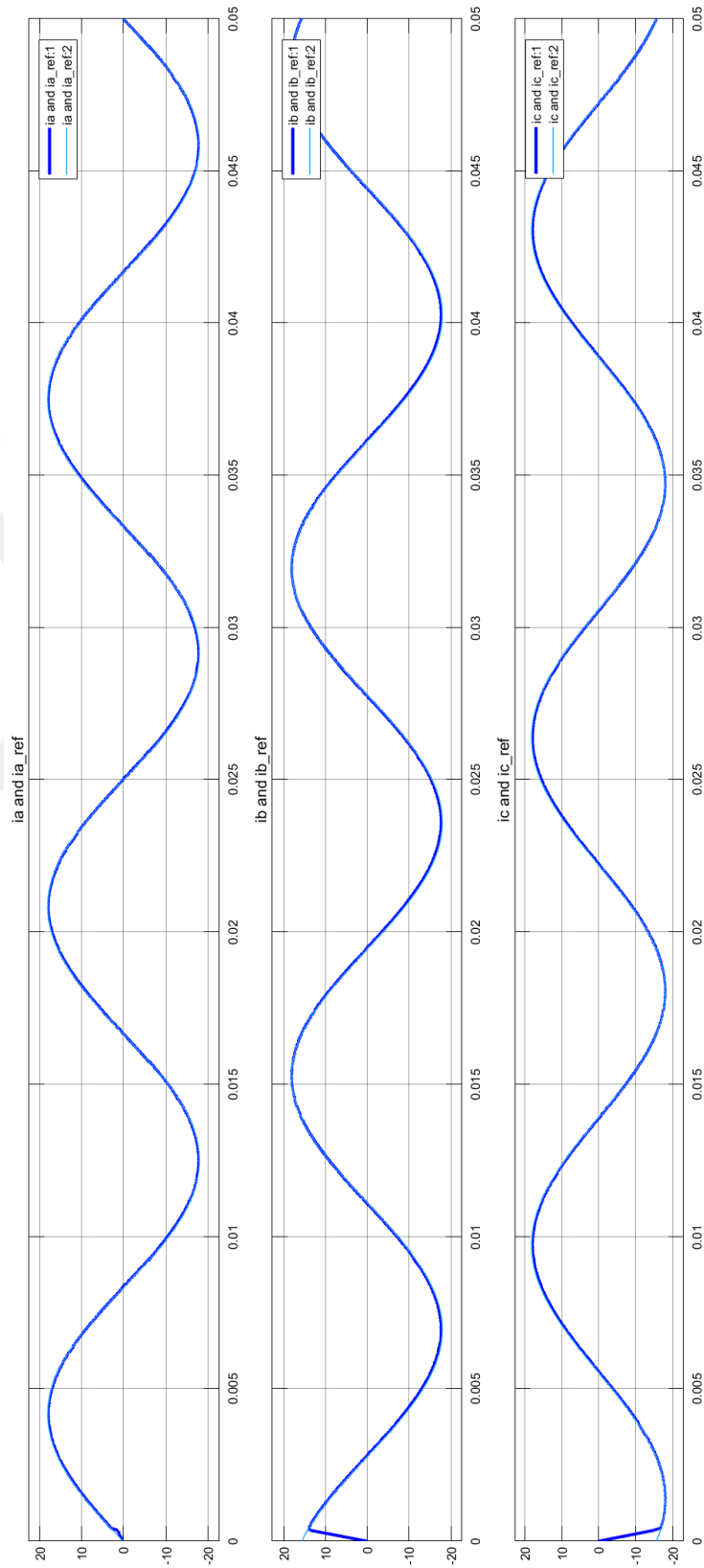


Figure 3.5: Current Tracking

We demonstrated that our methodology is able to track the phase currents, and $V_N^*(t)$. We selected current reference inputs as sinusoidal function with amplitude equal to 10, frequency equal to 60 Hz and the phase shift between them is equal to 120 degrees, and $V_N^* = 0.2 + \sin(10\pi)$. In both current subsystems, reference and real currents coincide. Average value of V_N is equal to zero after the transient caused by the initial condition equals to 10.

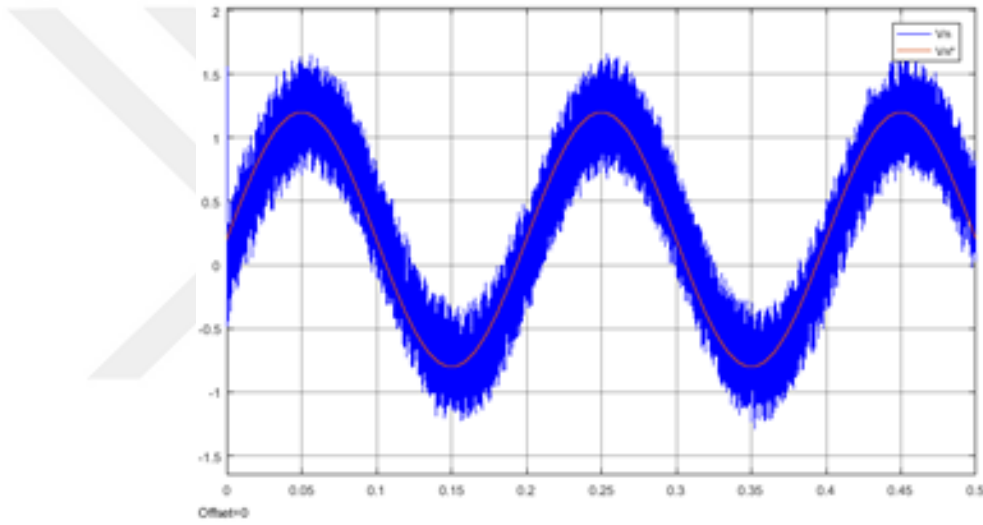


Figure 3.6: Average Value of Neutral Voltage Tracking

The next set of simulation demonstrates decreasing some of frequencies by adding V_N^* in correspondence with the formula 3.19, if $g_1 = 0.4$, $g_2 = g_3 = -0.2$ are selected constant and $\frac{V_{dc}}{3L} = 1$, $V_N^* = -0.8$. In simulation we selected -0.75 . This case is shown in 3.7 and 3.8. As it can be seen that the switching frequency for g_1 remains approximately same, but for g_2 and g_3 it was decreased considerably and as result we observe considerable decreasing of some of frequencies.

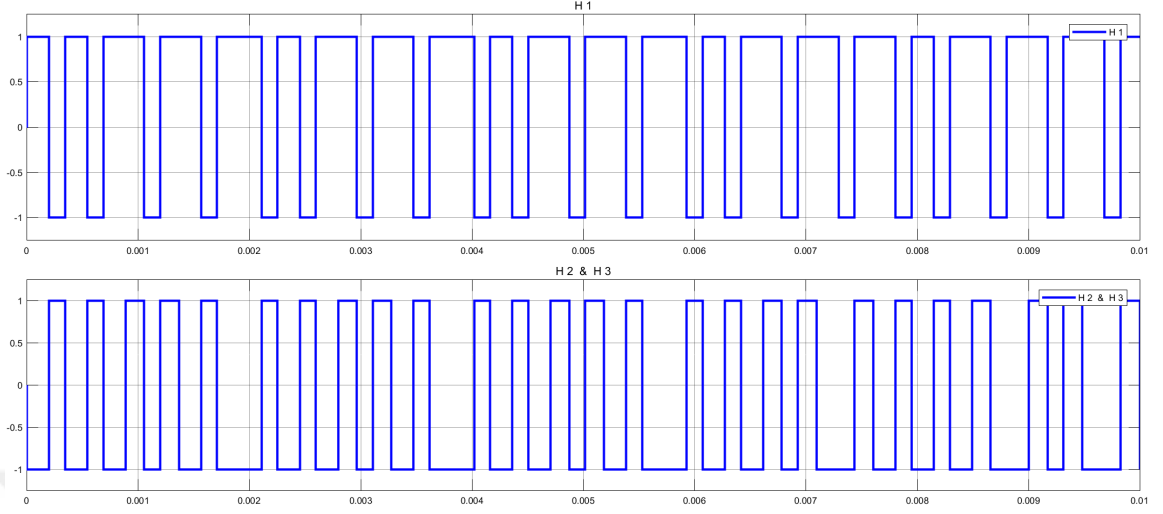


Figure 3.7: Switching Frequency with $V_N^* = 0$

The final set of simulation is performed to demonstrate the frequency reduction only. For this purpose, $g_1 = 0.5$, $g_2 = g_3 = -0.25$ are selected constant and $\frac{V_{dc}}{3L} = 1$. We assumed that $V_N^* = 0$ the frequency of $g_2 = g_3$ corresponds to maximum admissible value. (see ??). As it is expected, the frequency of g_1 is lower than g_2 and g_3 . Then, we add some negative V_N^* value where all points such that their frequencies are equal.

$$g_1 - V_N^* = \left| g_2 - V_N^* \right| \quad (3.20)$$

Since g_2 is negative, V_N^* can be calculated as -0.125 .

Select $V_N^* = -0.125$ (Figure 3.9), as you can see all three frequencies are the same and lower than the maximum admissible frequency.

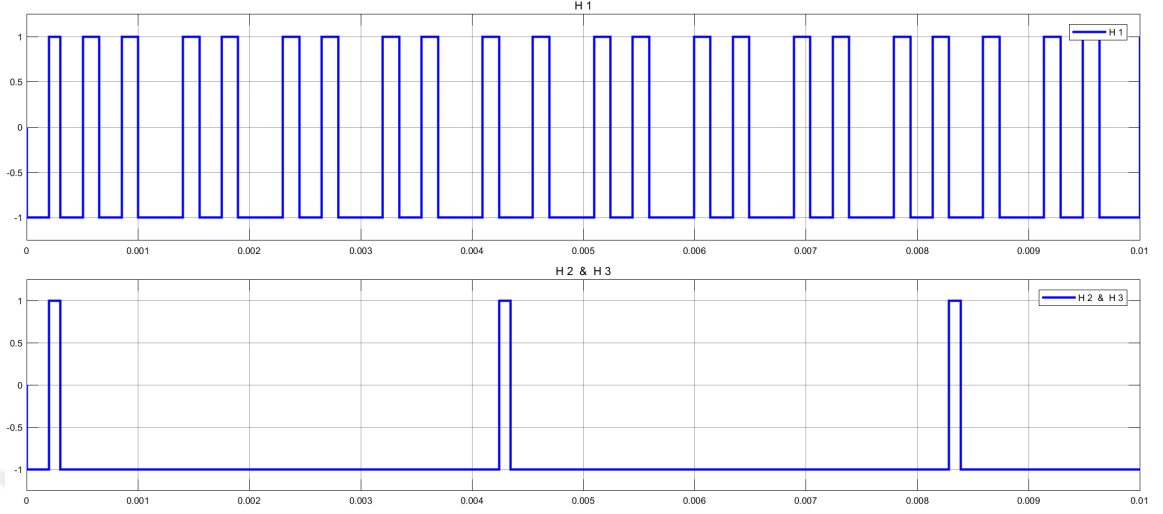


Figure 3.8: Switching Frequency with $V_N^* = -0.75$

Considering the 3.4 and the equation 3.19, we select $V_N^* = -0.125$. We demonstrated that the sum of the frequency can be decreased. We also showed that the sum of the frequency with varying V_N^* is lower than $V_N^* = 0$, as it was expected.

In this simulation, hysteresis width is selected such that one of the phase frequency equals to maximum admissible frequency level when $V_N^* = 0$. This means that hysteresis width cannot be decreased. The objective of frequency control is decreasing the sum of phase frequencies by changing V_N^* . If it is lower than admissible value, then hysteresis width can be decreased to increase accuracy. As a result, the width of the hysteresis loop can be decreased and the accuracy can be improved.

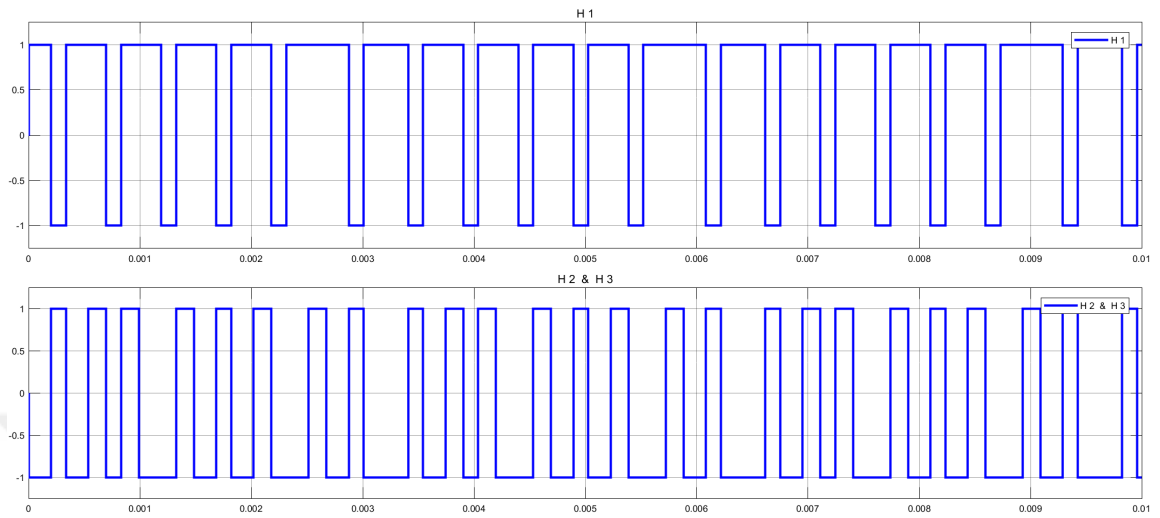


Figure 3.9: Reference Neutral Voltage is Zero

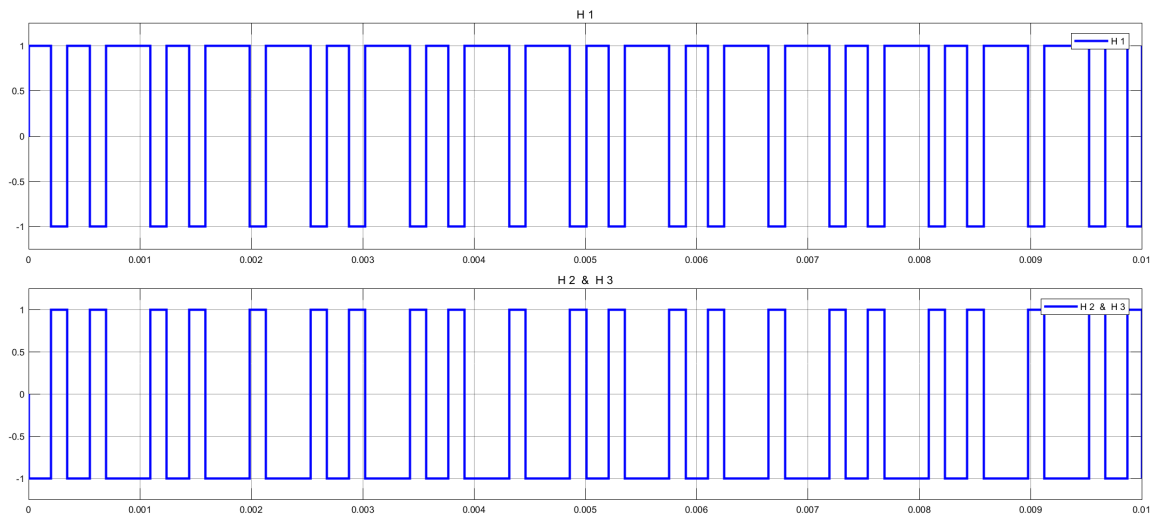


Figure 3.10: Reference Neutral Voltage is -0.125

Chapter 4: SLIDING MODE SELF-OPTIMIZATION OF THREE-DIMENSIONAL PARTICLE TRACKING SYSTEM BY INTEGRATION OF AN ELECTRICALLY FOCUS-TUNABLE LENS

Microscopes ushered in new epochs since its invention in during 1590s with opening the microscopic world's doors to scientist. Since then microscopes have been used in various areas but mainly in biology, fluid mechanics, colloidal science and so on. Advances in microscope competence and quality of images have never been found sufficient, though superior microscopes have been presented to answer the demand. Especially the movement of many infinitesimal biological phenomena and particles cause out-of-focus images and then decent observation becomes impossible. Thereby, in some applications, it is required that microscopes must track corresponding particles that exhibit mobility in direction beyond the plane of stage, nevertheless microscopes are still designed to have static focus. Previously, moving the microscope lens and/or stage are accepted as a common solution. However, these propositions have not go an efficient settlement to nature of the problem. Furthermore, slower mechanical response time compared to movement speed of the particles, limited physical space for movement under the microscope and mechanical vibrations due to movement are

critical drawbacks of proposed techniques. These complications require completely different solution method(s) and Electrically Tunable Lens (ETL) offers brand new approach.

An electrically focus tunable lens are invented to solve the automatic focusing of moving biological particles. Optotune's elastic polymer material made shape changing lens is designed to serve for this purpose 4.1.

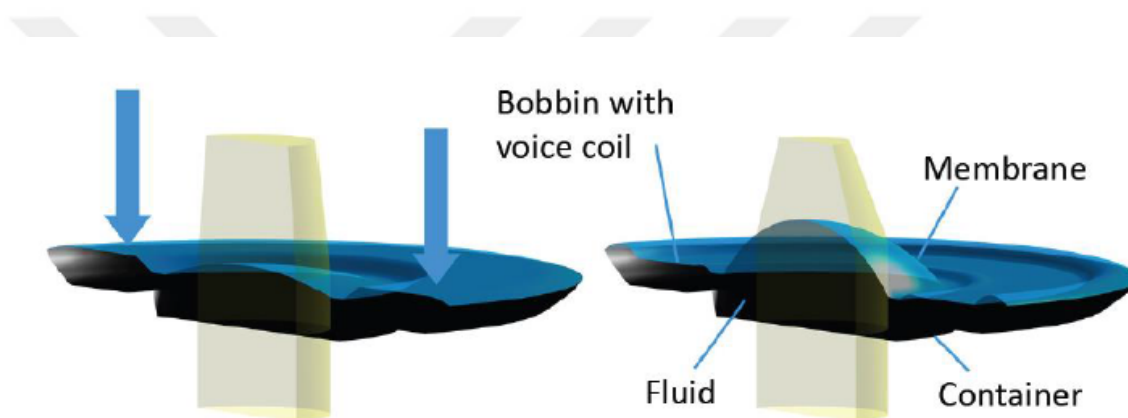


Figure 4.1: Scheme of the sealed lens container filled with an optical fluid and embedded in an EL-16-40-TC housing

The lens consists of thin membrane, optical liquid-filled chamber with voice coil. Bobbin with voice coil is connected to a current controlled electromagnetic or mechanical actuator which exert pressure on the optical liquid filled chamber and changes curvature of the lens. The optical power of the lens changes along with amount of positive or negative current flowing through the coil, where optical power (focusing power) means the degree of a lens, mirror, or other optical system converges

or diverges light [24] and its SI unit is inverse meter or also called dioptre. Therefore, electrically tunable lens (ETL) requires effective control algorithm to apply on the current controller or lens driver to provide adequate amount of the current to voice coil. The optical power range of the EL-16-40-TC is given below as an example 4.2

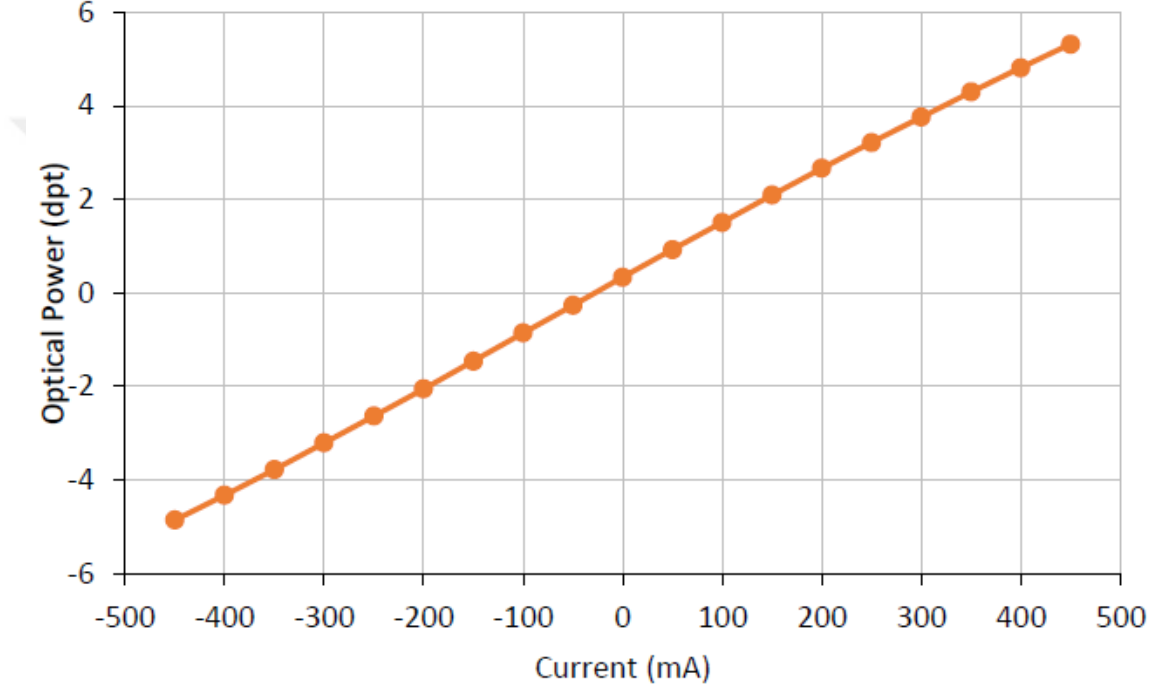


Figure 4.2: relation between optical power and electrical current

Microscope can be modified with a piezo stage implemented on top of the its manual spacial stage to obtain three-dimensional motion. Thus, sub-nanometric precision motions became obtainable in all x , y and z directions. Piezo stage has significant role with controlling particle position, z_p , in the automated calibration process along with reference trajectory verification to preferred tacking algorithm.

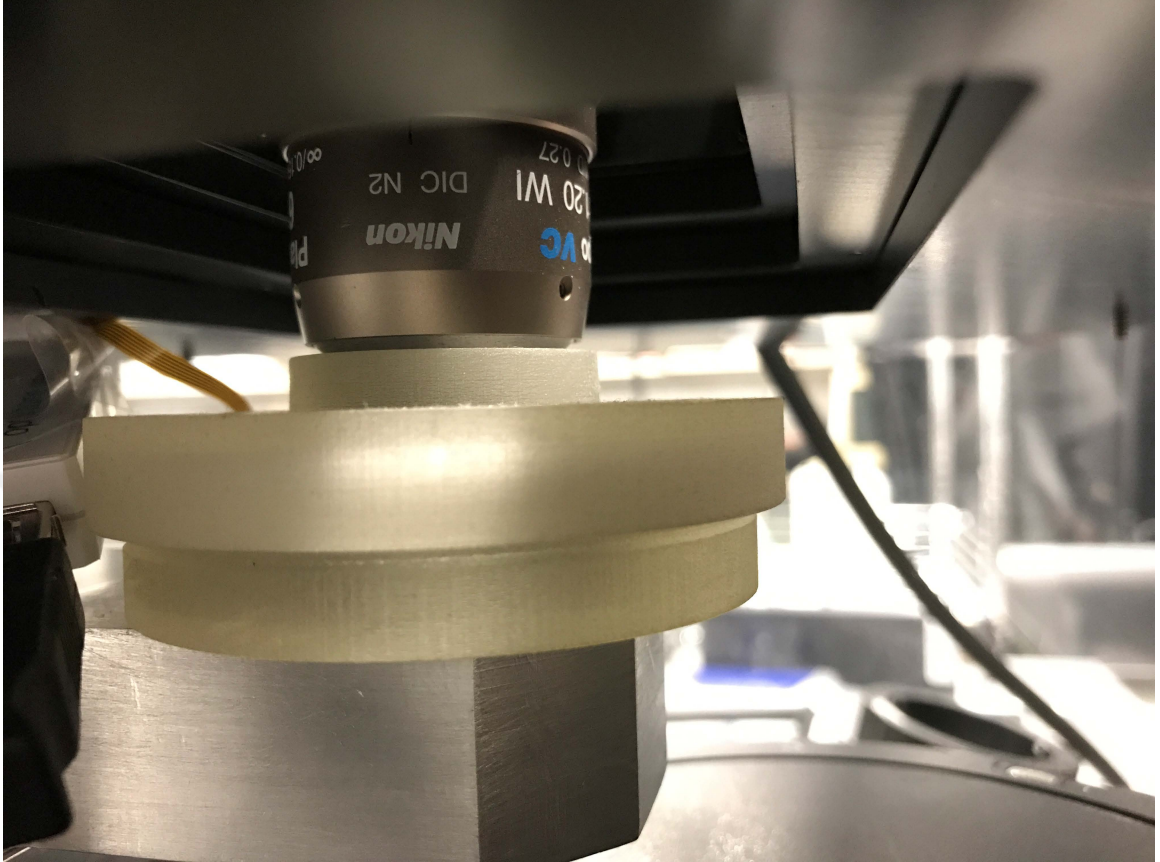


Figure 4.3: Basic Working Principle of Optotune's ETL

Control design of the auto-focusing system has essential boundaries to be considered in terms of complexity and cost. Focal length is the only degree of freedom to be varied for most tunable lenses, unlike the spatial light modulators and deformable mirrors used in sophisticated microscope applications. Note that a microscope alone with single electrically tunable lens would be inadequate to cope with sophisticated aberration corrections and cannot perform proficiently as an adaptive optics microscope in a remote focusing path, but using ETL in combination with appropriate control algorithm can achieve the objective of tracking the particle in

auxiliary direction. On account of that, proper control algorithm allows microscope to use its at most capacity. The first control algorithm that comes to mind is a linear PI controller. T. Agarwal's work [6] clearly shows the need of elaborate calibration to achieve tracking, which is to be tuned up each time before performing tracking, because the models and its parameters change depending on optical conditions. However, sliding mode self-optimization control algorithm has a fortunate advantage in such situation requires unceasing calibration. It is capable of achieving tracking objective without the need of any model calibration. Besides, as is known, sliding mode control algorithm offers remarkable properties of accuracy, robustness, easy tuning for implementation under uncertainties, which makes it proper control method regarding nature of the problem. Hence, a computer controlled auto focusing system with using electrically tunable lens is designed based upon sliding mode control and image processing.

4.1 Control System Design

The centroid method is widely accepted accurate, robust and fast technique that is used to estimate the circular particle's x and y axis positions from two dimensional images obtained from microscope's camera. Image is represented as single large matrix with elements of numbers specify colors and intensity of corresponding pixel on the image. In this technique, it is assumed that the center of bead coincides with centroid image. Besides, image processing process is required to eliminate or decrease estimation errors caused by non-uniform background noise. This requires normalization of image matrix obtained from camera with extracting a small region of interest,

which is why it is called estimation of particle position. Particle's image boundaries are obtained by the help of MATLAB software, which implements Moore-Neighbor tracking algorithm modified by Jacob's stopping criteria [55].

The centroid method estimates the x and y positions of the particles by using estimated particle boundary. Then position of the bead equals to coordinate of the centroid (x_c, y_c) , which can be calculated by

$$(x_c, y_c) = \left[\frac{\sum_{x=1}^W \sum_{y=1}^H x \times I(x, y)}{\sum_{x=1}^W \sum_{y=1}^H I(x, y)}, \frac{\sum_{y=1}^H \sum_{x=1}^W y \times I(x, y)}{\sum_{x=1}^W \sum_{y=1}^H I(x, y)} \right] \quad (4.1)$$

where H is number of rows in image intensity matrix, W is number of columns in image intensity matrix and I is intensity of the image.

Motion of the particle is three dimensional. The estimation of lateral position in the image provides particle tracking in x and y directions via centroid method. However, for an instance, if the particle moves along the z direction, out of the planar observation plane, lateral particle tracking will instantly disappear. Therefore, lateral particle tracking becomes trivial besides to more essential axial direction particle tracking. Namely, three dimensional particle tracking can only be succeeded by achieving efficient axial tracking method. The axial position can be controlled by shifting focal point through electrical current input fed to voice coil. The purpose of axial tracking is to coincide focal plane with particle position.

Electrically tunable lens equipped microscope's control systems suffer from inadequate direct feedback of focal plane z -axis position. The output camera image is

the only possible information to be used as feedback. Digital image processing transforms excessive length of image matrix to workable degraded scalar value represents focal position of the particle. Difference between the focal plane and particle position is used as a part of quadratic function to be maximized with using self-optimization sliding mode control algorithm. Objective of the control design is simply to make vanish the difference between position of the particle and position of the net resultant focal plane rapidly.

$$error = \Delta z = z_p - z_f \quad (4.2)$$

where z_p is z axis position of the particle ($\mu m, z_p \in [0, 20]$), z_f is z axis position of the net resultant focal plane (μm) and Δz is the difference between z axis position of the particle and focal plane (μm).

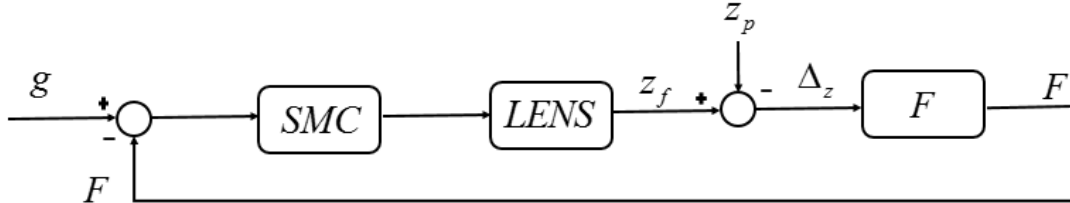


Figure 4.4: Control Design Schematics

Sliding mode control (SMC) is only deal with one dimensional (z -axis) optimization. The control design is simply illustrated in 4.4, where SMC self-optimization switching element controls lens with providing necessary input current and output of

the plant tracks monotonously increasing function g while approaching the maximum point. Sliding mode appears when the difference vanished between the output and monotonously increasing reference function. Focal plane, particle position and the plant gain are unknown in our system, thus it will result positive feedback in one branch of the extremal curve, where the output signal cannot track the reference input g . Hence, the conventional relay function is replaced with relay system consists of two surfaces in order to preserve sliding mode. Sliding mode appears either one of them, then eventually the extremum point is reached. In the course of approaching extremum point gradient tends to zero and sliding mode disappears. Hence, special function introduced to restore initial conditions, in this way output is hold steady on the extremum level with certain chattering. Details of the control algorithm is addressed in Chapter 2.

The output of microscope is an image of the particle which is interpreted as a large digital matrix, is not in a suitable form to work with in short sample time. Furthermore, aforementioned sliding mode static self-optimization algorithm finds the maximum or minimum of a quadratic function and therefore it requires a scalar input value. Thus, a large image matrix should be reformatted and represented as a single scalar value by a specific function. Finding the appropriate metric for the auto focus algorithm that has a quadratic relationship with the error, Δz , is a critical task for this implementation. Among many presented metric functions in the literature, a function, F , is found convenient for this application. It is evaluated from the image matrix which is a sharpness metric of the image based on its normalized variance. z_p and z_f are both unknown variables, but their difference, Δz is a function of F . F

function evaluated from image matrix gives a distinct maximum when the image is in focus.

$$F = \frac{1}{H.W.\mu} \sum_{y=1}^H \sum_{x=1}^W (I(x, y) - \mu)^2 \quad (4.3)$$

where H is number of rows in image intensity matrix, W is number of columns in image intensity matrix, μ is the average of the image intensity matrix, and I is intensity of the image. Function F has a maximum point when the image is in focus. The validity of this function is experimentally tested by Tushar Agarwal [6] where Δz is varied from -2 to $2\mu m$ for chosen different z_p . Each curve has distinct maximum value when Δz equals to zero 4.5.

The purpose of self-optimization sliding mode control algorithm is to maintain output of the function F at its maximum. Although manufacturer of the lens provides current versus focal plane graph, in order to implement the accurate control design, the system design dynamics has to be evaluated which requires model calibration. This relationship is evaluated by using experiments. Because, the plant receives current as an input and gives an output z_f as a dynamic response, where these dynamics have been assumed to be at first order with a time constant of 15 ms. Thus, the relationship between input current to lens coil ($mA, i \in [0, 292.84]$) and z_f is required. T. Agarwal did quasi-static calibration for a range of $\pm 0.4\mu m$ with equally spaced intervals from $1\mu m$ to $15\mu m$. In each trial, sharpness metric F is maximized by using golden section search 4.6, which brings each sample image in focus. Position of the particle is known, thereby z_f is found. Experiment results are plotted in Figure 4.6 which shows the quasi-static relationship between i and z_f .

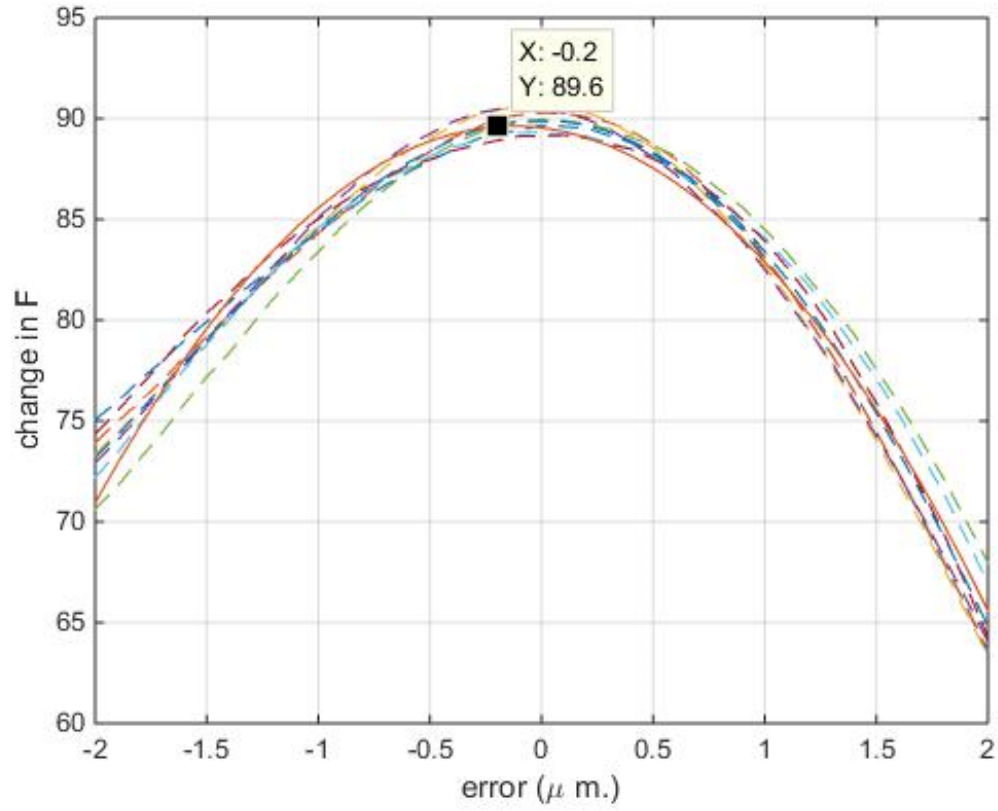


Figure 4.5: Change in Focus Plane

General equation of this line is of the form:

$$i = a_1 z_f + a_0 \quad (4.4)$$

The lens transfer function, G , has a gain of a_1^{-1} to incorporate the magnitude conversion lens input current, i to position of the net resultant plane z_f with a time constant $\tau = 0.015s$ in continuous time.

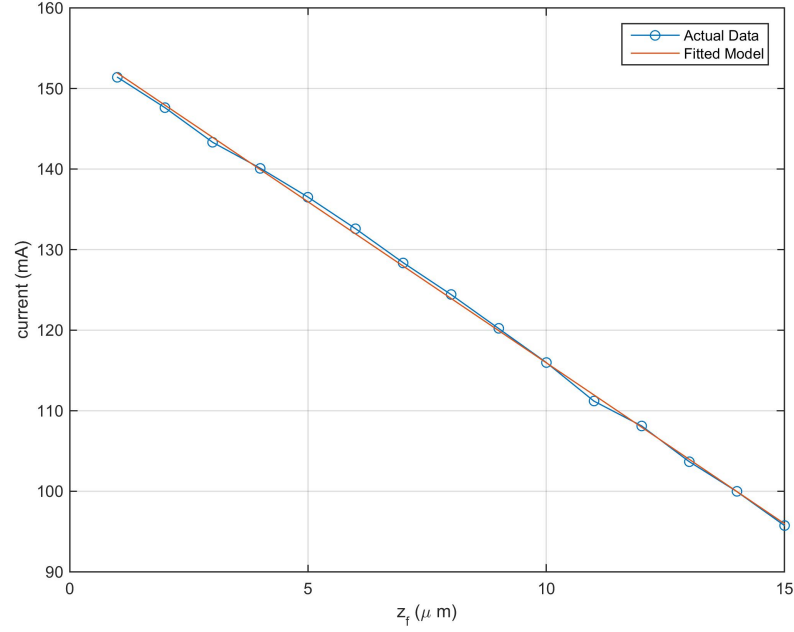


Figure 4.6: Model Calibration Result

$$G(s) = \frac{1}{a_1(\tau s + 1)} \quad (4.5)$$

a_1 is assumed equal to the slope of i vs z_f in Figure 4.6, which approximately equals to -60 . Previously presented self-optimization control algorithm has a single control input u connected to integrator creates scalar input to plant function. However lens' transfer function is different than an integrator. Presented method implies inserting integrator which makes system in second order, hence sliding mode cannot exist in principle. Since order of the system is one, it is used as an integrator in our methodology. Even if gradient procedure requires an exact integrator, since our

method is based on tracking, it can be used for any type of first order system. This is an important advantage of the method.

4.2 Design and Simulation Results

Metric of sharpness function F is obtained among various functions presented in [59] to model and estimate Δz explained in section 4.1. Even though this function is applicable for experiments, it is interpreted for simulation purposes as

$$F = -\alpha(\Delta z)^2 + \beta \quad (4.6)$$

where α and β are selected as 10 and 90.

The digital control system is implemented on Matlab&Simulink software. Transfer function of the lens is found in the first order in continuous time with a time constant of $\tau = 0.0015s$ and a_1 is assumed to be -60 which is approximately the slope obtained from i vs z_f curve. The initial conditions of the particle position and position of the net resultant focal plane are both $4\mu m$. Triangular disturbance amplitude of $2\mu m$ with the frequency of 0.1 Hz. The model is given in Figure 4.7

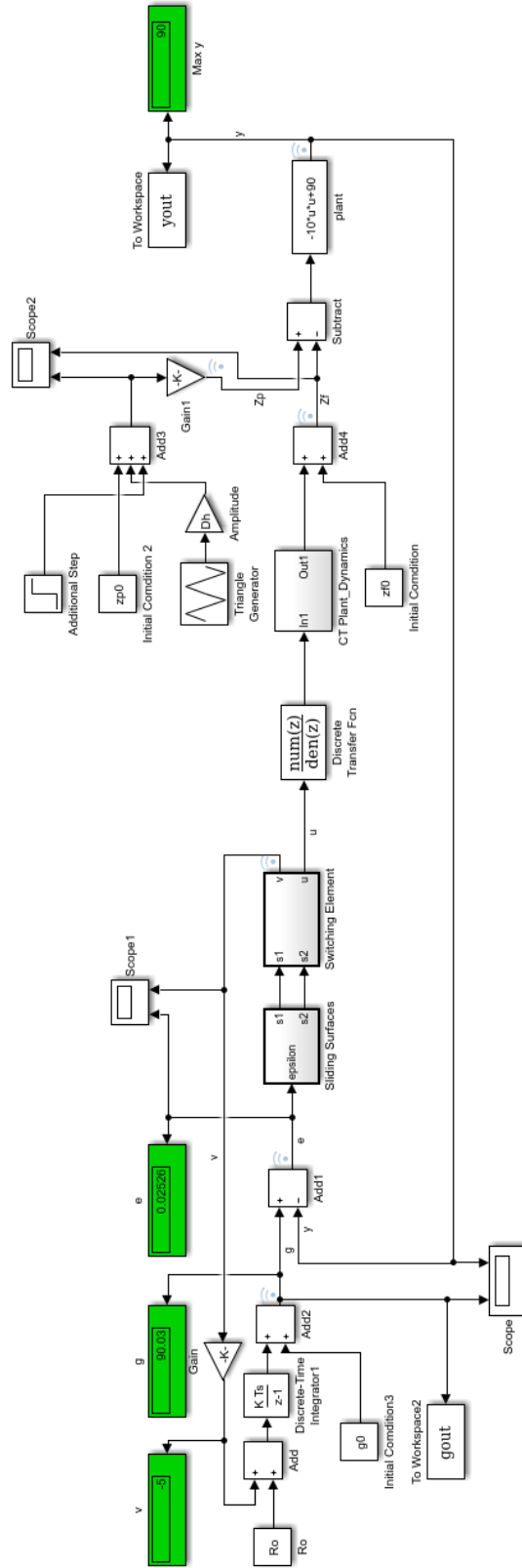


Figure 4.7: Simulink Model

The output of sharpness function F tracks monotonously increasing g function as shown in Figure 4.9. According to introduced self-optimization algorithm, sliding mode appears for special initial conditions between two switching surfaces. SM occurs either one of them, then tracking is performed with monotonously increasing function. The distance between sliding surfaces is selected as $\delta = 0.5$ and hysteresis width is $\Delta = 0.025$. Sliding mode appears when monotonously increasing function equals to output of sharpness at four seconds. Sliding mode disappeared in the vicinity of extremum point where exact tracking starts after 43 seconds.

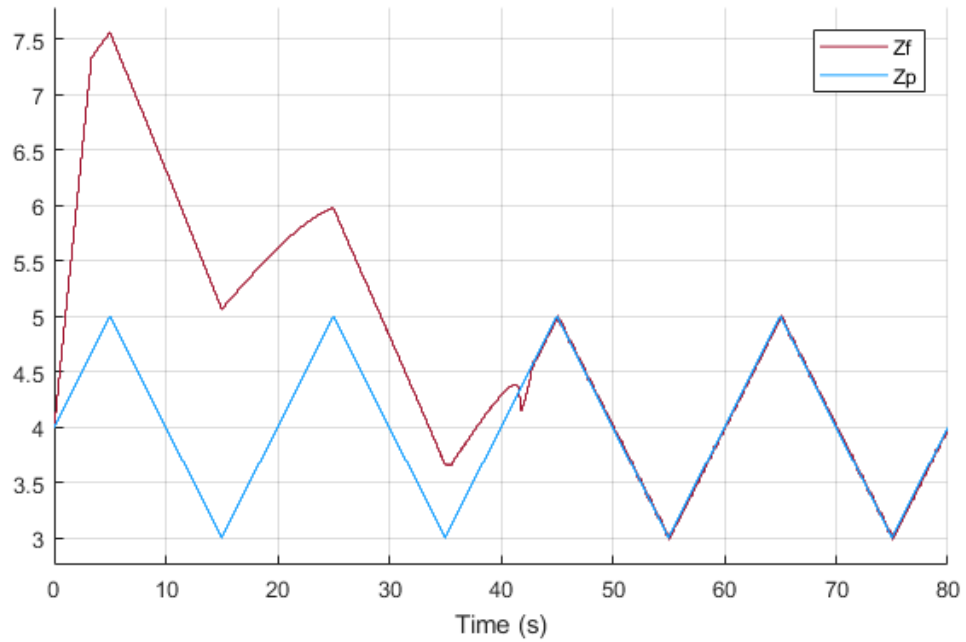


Figure 4.8: Particle Tracking

The sliding mode control self-optimization algorithm tracking works successfully as shown in Figure 4.8. Position of the net resultant focal plane starts tracking the particle position after 43 seconds.

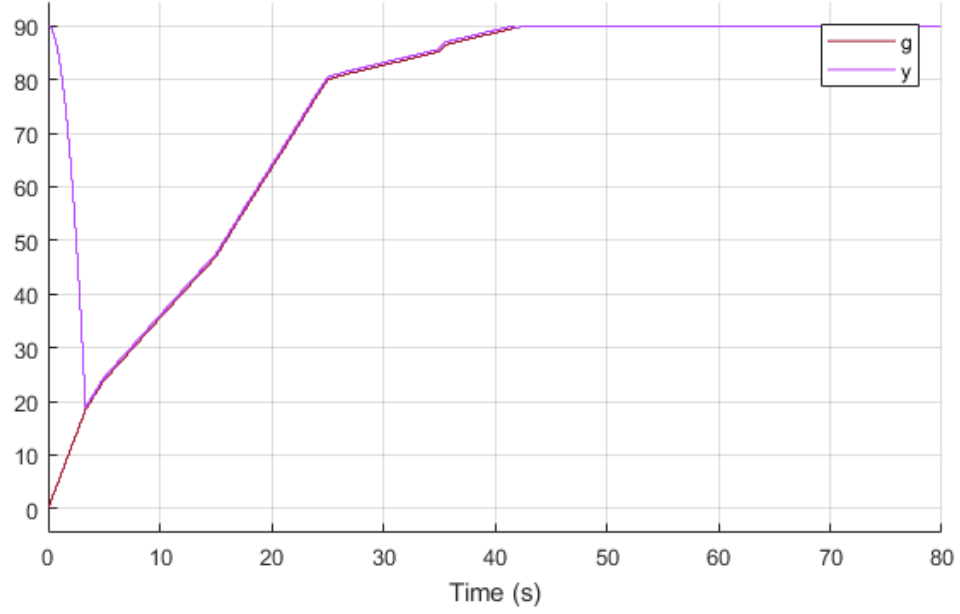


Figure 4.9: Output Tracking

Simulation is performed in discrete time because real experimental setup consists of microscope and assisting computer system works in discrete time. The hysteresis width is selected equal to microscope sampling time interval which is very high, 0.14s and leads to chattering problem. Because the width of hysteresis loop should be higher than amplitude of chattering.

Sliding mode disappears when the output reaches certain vicinity of the extremum. Thereafter, special function v is activated to restore existing conditions. Sliding surface switching is shown in figure 4.10

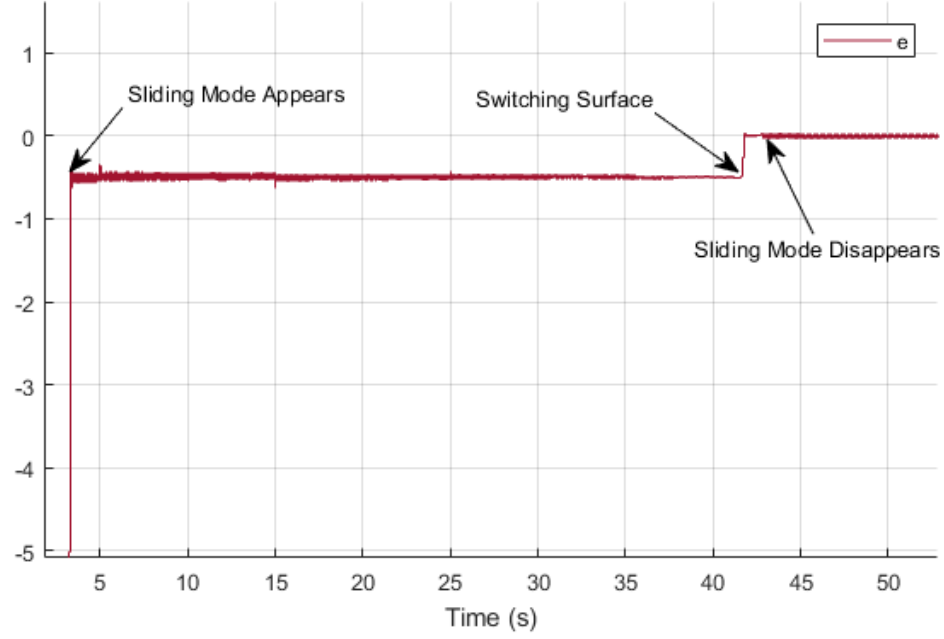


Figure 4.10: Sliding Surface Switching

Sliding mode self-optimization technique offers efficient tracking results with 0.001 sampling time. SMC three dimensional tracking starts properly after 43 seconds where linear PI control algorithm option provides it in a few seconds [6] with 0.14 seconds of sampling time. SMC self-optimization technique takes more time for convergence than PI control types.

Accuracy of the algorithm does not depend on the distance between surfaces, but it is only determined by the width of hysteresis loop, which is dictated in terms of chattering amplitude, sampling time and it cannot be selected less. The self-optimization algorithm provides best achievable accuracy.

PI control models are tuned for a small range of distinct applications which requires recalibration before every tracking. This causes waste of resource and time. On the other hand, SMC self-optimization does not need any calibration, that makes it universally applicable for any amount of range that experimental setup allows. This makes SMC self-optimization technique more robust over others. Even so every single application dictates which among two is more suitable to real life, unlike PI control technique, SMC self-optimization method does not require model and it still tracks particles efficiently.

Chapter 5: SLIDING MODE SELF-OPTIMIZATION FOR UNDERGROUND COAL GASIFICATION (UCG) PROCESS

More than a century ago, coal was main energy source for heating, illumination and production of goods. Later, industrialization forced vast consumption of coal which soon afterwards falls short to meet the demand. Then, inevitably new energy sources and technologies appeared on stage over time, such as hydroelectric power, nuclear and renewable energy sources. Nevertheless, irresistible increase in power demand brings along efficiency enhancing of current power generation methods and exploring new kinds of sources. Notwithstanding supplying affordable energy and obtaining without polluting environment are essential variables of the power policy equation. Increasing awareness of acquiring clean energy left no choice but restoring conventional technologies. Therewith, it is also politically crucial to diversify options of energy generation. Consequently; political issues, finance, green energy concerns and so forth parameters created multiple dilemmas to be discussed by each fragment of the society.

In general, power generation methods objected to be reliable, efficient, economically feasible for production and investment. Power generation could be breaking up into six main branches; coal, natural gas, petroleum derivatives, nuclear, hydro-electric and renewable power plants. Despite the fact that, coal reserves in the world approximately equals to two thirds of petroleum and 1.5 times of natural gas reserves, it has been consumed under its potential due to its voluminous nature and environmental pollution reasons. At the same time, last two decades of petroleum and natural gas price trending indicates that their price are predicted as 4 times expensive than today. Therefore, leading and developing countries, which craves more energy sources, need to diversify their options, secure corresponding expenditures, surely, compromising with environmental concerns. Bare into mind the advantages of renewable energy, massive amount of coal mines deserve new strategies to appreciate the benefit of such potential. Although west Europe countries abstained to appraise coal mines because of the financial, political and environmental reasons, United States and developing eastern countries like Japan and South Korea foresee coal as an inevitable long term energy source.

5.1 Conventional Power Station

Conventional power stations mostly burn coal or natural gas in large furnaces to produce electricity. The efficiency of these power stations is around %40. After all technological advances on increasing stream parameters with using better materials and designing bigger low pressure steam turbines to absorb exhausted steam heat, the efficiency is boosted only around %55, where such efforts could not put forward

financially bright results. Furthermore, environmental concerns and relevant required prevention investments are farther disadvantages. Many countries believe the merits of Kyoto protocol and legislated carbon emission limits for hazardous SO_2 and NO_x gases. Herein, it should be noted that filtration system causes additional investment expenses that increases total costs by one third and operating costs rebound production unit price by 1.5-2.5 cents/kWh where current average unit price is already around 5-7 cents/kWh. However, on the contrary to conventional coal power stations, natural gas burned power stations do not require such filtration investments due to its production technology does not output those hazardous gases. On the account of investment costs, conventional natural gas power station is around 700 US\$/kW where conventional coal power station is between 1300-1500 US\$/kW including additional investments for filtering hazardous gases [15]. Along with mentioned reasons, recent increase in environmental awareness resulted in advances new technologies in energy generation from coal mines.

All in short, many countries turned into alternative energy sources and new technologies like coal gasification technology, introduced due to following reasons listed

- Conventional energy sources (petroleum, natural gas, nuclear) are running out
- Environmental concerns
- Increasing unit price of current energy sources due to investment, transportation, supply and disposing expenses
- Uneven distribution of energy sources per territories/countries

5.2 Underground Coal Gasification (UCG) Plants

Vaporization of solid fossil fuels into distinct gas products by heterogeneous chemical reactions is called gasification. Commonly used gasifiers are steam, air, H_2 , CO_2 and O_2 . Coal gasification is commonly used for meeting chemical needs like ammonia, methanol, synthetic liquid fuels which can be used for energy generation. The amount and compound of the products vary according to nature of the coal and applied process consists of temperature, pressure and gas flow. Product mixture of the coal gasification are CO, CH_4 , H_2 , CO_2 , N_2 , H_2S , COS constitute the raw output material which is required further chemical decomposition. Coal gasification is applied to steam turbines after redundant particles are combed out and polluting useless gases are filtered from the output product. There are three different commercial coal gasification used process

- Fixed-bed
- Entrained-flow
- Fluidized-bed

Underground coal gasification (UCG) is one of the new technology became well-settled method used for generating electricity from burning gasified coal. It is developed from conventional coal thermal plants where obtained synthetic gases (CO , H_2) from coal are used to supply electricity with minimum pollution. UCG process is commonly applied on low calorific or geologically difficult mines which have volcanic, high breaking frequency or tectonic natured places [15]. This method does not require

complex technological reactors, because coal stratum performs as a reactor under the ground. Acquired oxidation product, syn-gas, is used for electricity generation by integrated gasification combined cycle (IGCC) stations or it can be utilized for liquid fuels and specific chemical products by Fisher-Tropsch (FTS) methods. FTS process provides clean diesel fuel, jet-fuel, ethanol, methanol and other important products. UCG does not require ash, slag removal because process uses underground cavity as a reactor and also a storage. Besides, it allows to store heat and gas available to use when needed. Heated underground water helps to keep reactor warm, thus temperature loss significantly becomes less. Existing pressure providing minimum environmental pollution with easing chemical reaction. On the other hand, obtained CO₂ can be stored in drained petroleum and natural gas reservoirs (geological sequestration) and it can be evaluated by Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR) process.

Feasibility examinations are required to test essential geological parameters like coal aging level, compound composition of the reserve, properties of earth stratum. Pilot well is used to obtain such information by three-dimensional area identification, underground hydro-geology modeling. Convenient field is considered feasible if coal layer width is between 0.5m-30m, coal layer span is between 100-600 m, slope is between 0-70 degrees, depth is between 30-800m, calorific value is between 1900-7100 kcal/kg, ash rate is less than %60, moisture rate is less than %40 and coal reserve average is around 100 trillion tons [15]. There are two different types of UCG process technology. The first method, Reverse Combustion Linking (RCL), is known as USSC technology, commonly used on high ash rated coal mines. Second method is tested in USA and Europe which uses enriched air and oxygen rates along with

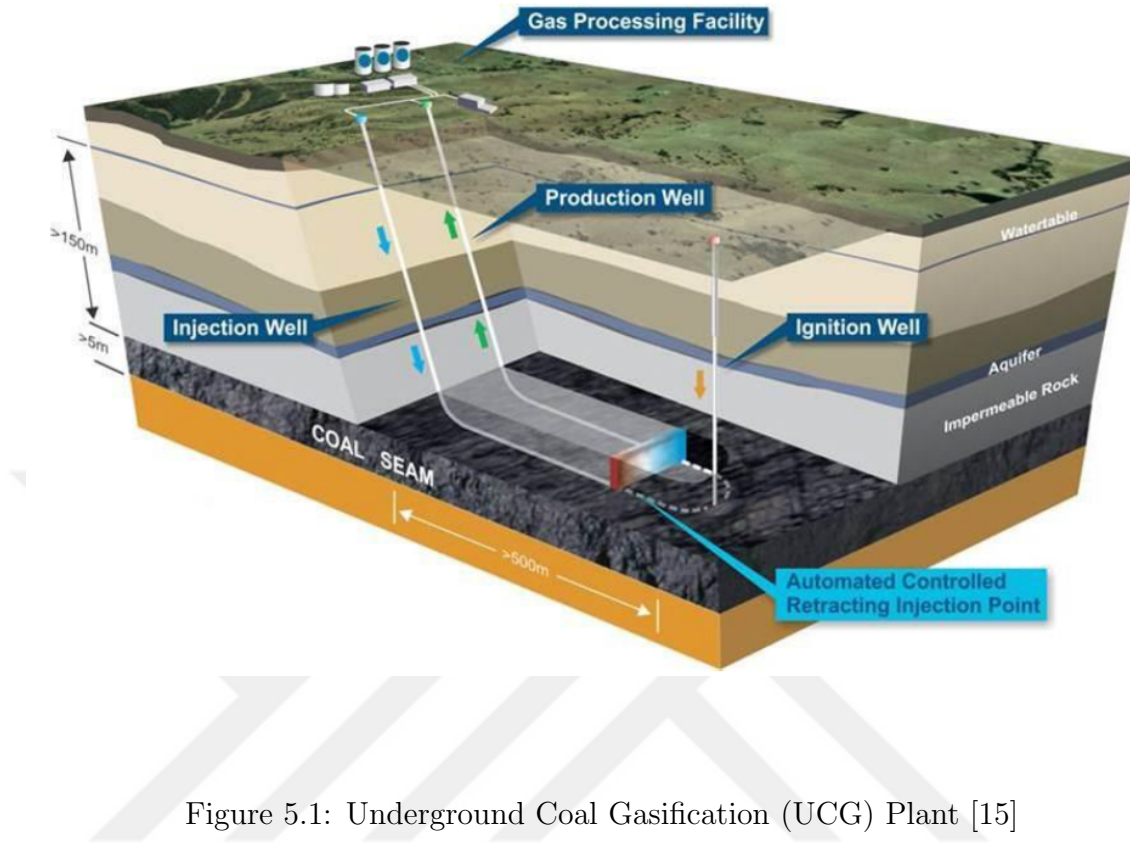


Figure 5.1: Underground Coal Gasification (UCG) Plant [15]

sensors planted around the coal layer which can detect cracks, pores and fractures in the coal layer and provide high efficiency process control.

5.3 Problem Statement

The control design of Underground coal gasification (UCG) process provides its maximum possible efficiency when maintaining the heat value at desired range constantly under the inevitable inaccuracies and disturbances. The plant reactor operates under the ground, which makes impossible to obtain any sensor feedback information required to design more robust system. The produced gas flow is the

only possible data to be used for design. Complex geometry of the reactor and highly nonlinear nature of model require hearty sophisticated control design which conversely makes process complicated to operate along with inevitable investment costs. Thus, it is crucial to obtain best achievable efficiency with the simplest possible model under the uncertainness and disturbances, which makes control design even more challenging.

In this study, previously introduced model [4] is used. Purpose of the control is make vanish the difference between output gas flow, y , and preset reference value, y_r . Previously, sliding mode control (SMC) technique was used to operate UCG process in [8] and [5] in order to keep the reactor's heating value at the desired constant value. Besides SMC's essential properties that offer robust, accurate results under disturbances and state uncertainties, make it proper candidate upon considering nature of the problem. Effect of varying inlet O_2 and steam ratio was studied with only three examples in [8]. It is concluded that the increase in O_2 results inflation of reactor temperature because of the increased exothermic char oxidation reaction. Besides, the conversion rate of coal overtake char by the increasing temperature. Even though the rate of O_2 is crucial to provide required heat through char oxidation reaction, it also produces higher CO_2 which decreases the heating value of the product gas. Therefore, this dilemma naturally brings along the problem of finding maximum possible rate of O_2 value, which is surely increase the efficiency of UCG process.

The output gas flow rate, y , depends directly on the control of oxygen rate where it should be calculated such that output gas flow equals to desired value. However, oxygen rate control function is unknown which to be maximized and this problem can be solved in the frame of sliding mode control. By the virtue of technique, sliding mode can be enforced even if the function is unknown. System model possess integrator and known desired output value to be tracked via discontinuous control. After reference input is tracked, remaining part of the system should be analyzed, which is called zero-order dynamics. In [8], required analyses are performed and stability of zero-dynamics was proven. Thus, this model is used with recommended simplifications for the simulations. Analytical analysis is very difficult due to great deal of high order differential equations and complex nature of UCG model, hence necessary simulations and experiments are conducted. Thus, entire chemical reactions along with simplified model equations, [5], in the total system are required to validate for tracking simulation instead of truncated distinct oxygen rate control function. Basically, maximization of output gas flow rate is interested from the point of technological perspective. The objective of this study is controlling rate of oxygen-steam with providing maximum output gas flow. Besides, control procedure is modified when the boundary of pressure actuator is tested with its limits, yet extremum point is searched until pressure value is within admissible range and oxygen-steam ratio is maintained at its optimum value.

Block diagram of sliding mode self-optimization design for UCG system is shown in figure 5.2.

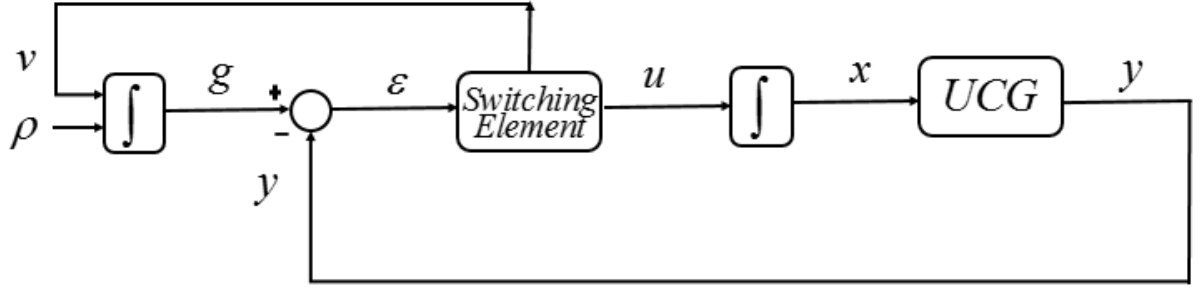


Figure 5.2: SMC Self-Optimization Design for UCG

In figure 5.2, SMC self-optimization switching element generates control input u fed to an integrator, which creates input for the plant and output of the plant tracks monotonously increasing function g while approaching the maximum point. Sliding mode appears when control unit makes difference vanished between the output and monotonously increasing reference function.

The plant gain is unknown in our system, thus it will result positive feedback in one branch of the extremal curve, where the output signal cannot track the reference input g . Hence, the conventional relay function is replaced with another class of switching element in order to preserve sliding mode. In figure 5.2, the switching element consists of relay systems which creates discontinuous control input u with two points of discontinuities. It creates two surfaces where sliding mode appears either one of them and with decaying reference input, sooner or later, the extremum point is reached.

Plant gain tends to zero while approaching into vicinity of extremum point and sliding mode disappears. Thus, control algorithm is modified with distinct function v with two hysteresis loops added. If the sliding surfaces have the same signs, this function will have opposite sign after a finite time interval and restores the initial conditions. Details of the control algorithm is addressed in Chapter 2.

5.3.1 Reactor Model Chemical Equations

UCG process consists of qualitative chemical reactions and model equations explain them, which are not directly used in the mathematical model. However, these reactions give picture of reactor nature. Each UCG reactor host significant consequent chemical reactions with CO , CO_2 , H_2 , H_2O , CH_4 , N_2 , O_2 , TAR, coal and char. Comprehensive explanation of the UCG model is presented in [4]. Mathematical description of the underground coal gasification (UCG) plant can be referred in two phases; solid and gas phase mass and energy balance equations.

Solid Phase: Antonio Lavoisier discovered the conservation of mass law in chemical reactions, which also explains the rate of solid density in the reactor. Coal and char constitute the solid phase elements where CO , CO_2 , H_2 , H_2O , CH_4 , N_2 , O_2 compose gas phase elements.

$$\frac{\partial \rho_i}{\partial t} = M_i \sum_{j=1}^9 a_{s_{ij}} R_j \quad (5.1a)$$

$$\rho_i(0, x) = \rho_{i_0}(x), \quad 0 \leq x \leq 1 \quad (5.1b)$$

where ρ_i is the density of i th solid (kg/m^3), R_j is the rate of j th chemical reaction $mol/m^3/s$, M_i is the molecular weight of solid component i kg/mol , x is the variable for length m , t is time variable in seconds and s_{ij} is the stoichiometric coefficient of i th solid phase in j th chemical reaction which is negative for reactants and positive for products.

Solid phase energy balance equation is given as

$$\frac{\partial T_s}{\partial t} = \frac{\frac{\partial}{\partial x} \left[(1 - \phi) k \frac{\partial T_s}{\partial x} \right] + h_T (T - T_s) - H_s}{C_s} \quad (5.2a)$$

$$T_s(0, x) = T_{s_0}(x), \quad 0 \leq x \leq 1 \quad (5.2b)$$

where x is the variable for length (m), T_s and T are the solid and gas temperature (K), ϕ is the coal bed porosity, k is the effective thermal conductivity of solids ($J/m/s/K$), h is the heat transfer coefficient ($J/s/K/m^3$), C_s is the solid phase heat capacity ($J/K/m^3$), H_s is the solid phase heat source ($J/s/m^3$)

Gas Phase: Pressure and temperature of the gas and its concentration change in the reactor as a function of the reactor's length due to chemical reactions and superficial gas phase velocity. Superficial velocity in porous media, is a hypothetical velocity of gas phase considered over whole cross sectional area by ignoring the solid phase [23]. Mass and momentum balance equations are given below

$$\frac{dC_i}{dx} = \frac{1}{u_g} \left(-C_i \frac{du_g}{dx} + \sum_{j=1}^6 a_{ij} R_j \right) \quad (5.3)$$

$$\frac{dT}{dx} = -\frac{1}{u_g C_g} \left[h(T - T_s) + H_g \right] \quad (5.4)$$

$$\frac{dP}{dx} = -\frac{u_g \mu}{2K} \quad (5.5)$$

$$\frac{du_g}{dx} = -\frac{u_g}{P} \frac{dP}{dx} + \frac{u_g}{T} \frac{dT}{dx} + \frac{RT}{P} \sum_{i=1}^8 \sum_{j=1}^6 a_{ij} R_j \quad (5.6)$$

where C_i is the concentration of i th gas mol/m^3 , u_g is the superficial gas velocity m/s , C_g is the total gas phase heat capacity $J/K/m^3$, H_g is the gas phase heat source $J/s/m^3$, P is the pressure (Pa), K is the gas permeability coefficient (m^2) and μ is the viscosity (Pas).

Chemical Reactions Various incessant chemical reactions follows each other in the UCG reactor. Sequence starts with pyrolysis reaction where coal (CH_aO_b) decomposes to char $CH_{\bar{a}}O_{\bar{b}}$, where the values $a, b, \bar{a}$ and $\bar{b}$ are determined for Lignite B coal of Thar field. After pyrolysis, four heterogeneous reaction occurs following each other as char oxidation, steam gasification, CO_2 gasification and methanation. Latter reactions are all homogeneous. Corresponding grading chemical reactions in the UCG which describe kinetics of the model are taken from [14].

Coal pyrolysis reaction rate is

$$R_1 = 5 \frac{\rho_1}{M_1} \exp \left(\frac{-6039}{T_s} \right) \quad (5.7)$$

where M_1 is the molecular weight of coal.

Char oxidation reaction rate is

$$R_2 = \frac{1}{\frac{1}{R_{c2}} + \frac{1}{k_y y_7}} \quad (5.8)$$

$$R_{c2} = \frac{9.55 \times 10^8 \rho_2 y_7 P \exp\left(\frac{-22142}{\tilde{T}}\right) \tilde{T}^{-0.5}}{M_2} \quad (5.9)$$

$$\tilde{T} = \beta T_s + (1 - \beta)T \quad (5.10)$$

where M_2 is the molecular weight of char and y_7 is the molar fraction of O_2 .

Steam gasification reaction rate is

$$R_3 = \begin{cases} \frac{1}{\frac{1}{R_{c3}} + \frac{1}{k_y y_4}}, & \text{if } y_4 - \left(\frac{y_1 y_3}{K_{E3}}\right) > 0 \\ \frac{1}{\frac{1}{R_{c3}} - \frac{1}{k_y y_1}}, & \text{if } y_4 - \left(\frac{y_1 y_3}{K_{E3}}\right) < 0 \end{cases} \quad (5.11)$$

$$R_{c3} = \frac{R_{c3}^+}{y_4} \left(y_4 - \frac{y_1 y_3}{K_{E3}} \right) \quad (5.12)$$

$$R_{c3}^+ = \frac{\rho_2 y_4^2 P^2 \exp\left(5.052 - \frac{12908}{\tilde{T}}\right)}{M_2 \left[y_4 P + \exp\left(-22.216 + \frac{24880}{\tilde{T}}\right) \right]^2} \quad (5.13)$$

where y_1 , y_3 and y_4 are molar fractions of CO, H₂ and H₂O, and K_{E_3} is the equilibrium constant for steam gasification reaction.

Coal gasification reaction rate is

$$R_4 = \begin{cases} \frac{1}{\frac{1}{R_{c4}} + \frac{1}{k_y y_2}}, & \text{if } y_2 - \left(\frac{y_1^2}{K_{E_4}} \right) < 0 \\ \frac{1}{\frac{1}{R_{c4}} - \frac{2}{k_y y_1}}, & \text{if } y_2 - \left(\frac{y_1^2}{K_{E_4}} \right) > 0 \end{cases} \quad (5.14)$$

$$R_{c4} = \frac{R_{c4}^+}{y_2} \left(y_2 - \frac{y_1^2}{K_{E_4}} \right) \quad (5.15)$$

$$R_{c4}^+ = \frac{1.15 \times 10^4 \rho_2 y_2^2 P \exp \left(- \frac{23956}{T} \right)}{M_2 + 0.014 M_2 y_1 P \exp \left(\frac{7549}{T} \right) + 0.21 M_2 y_2 P \exp \left(\frac{3171}{T} \right)} \quad (5.16)$$

where y_2 is molar fraction of CO₂ and K_{E_4} is equilibrium constant for carbon dioxide gasification reaction.

Methanation reaction rate is

$$R_5 = \begin{cases} \frac{1}{\frac{1}{R_{c5}} + \frac{2}{k_y y_3}}, & \text{if } (y_3)^2 - \left(\frac{y_5}{K_{E_5}} \right) > 0 \\ \frac{1}{\frac{1}{R_{c5}} - \frac{1}{k_y y_5}}, & \text{if } (y_3)^2 - \left(\frac{y_5}{K_{E_5}} \right) < 0 \end{cases} \quad (5.17)$$

$$R_{c5} = \frac{R_{c5}^+}{(y_3)^2} \left((y_3)^2 - \frac{y_5}{K_{E_5}} \right) \quad (5.18)$$

$$R_{c_5}^+ = \frac{\rho_2 y_3^2 P^2 \exp\left(2.803 - \frac{13673}{\tilde{T}}\right)}{M_2 \left[1 + y_3 P \exp\left(-10.452 + \frac{11698}{\tilde{T}}\right)\right]} \quad (5.19)$$

where y_5 is molar fraction of CH_4 and K_{E_5} is equilibrium constant for methanation reaction.

Water gas shift reaction rate is

$$R_6 = \begin{cases} \frac{1}{\frac{1}{R_{c_6}} + \frac{1}{k_y y_1}}, & \text{if } C_1 C_4 - \left(\frac{C_2 C_3}{K_{E_6}}\right) > 0 \\ \frac{1}{\frac{1}{R_{c_6}} - \frac{1}{k_y y_2}}, & \text{if } C_1 C_4 - \left(\frac{C_2 C_3}{K_{E_6}}\right) < 0 \end{cases} \quad (5.20)$$

$$R_{c_6} = \frac{R_{c_6}^+}{C_1 C_4} \left(C_1 C_4 - \frac{C_2 C_3}{K_{E_6}}\right) \quad (5.21)$$

$$R_{c_6}^+ = 3 \times 10^7 \phi C_1 C_4 \exp\left(\frac{-7250}{\tilde{T}}\right) \quad (5.22)$$

where C_1, C_2, C_3 , and C_4 are concentration rate of $\text{CO}, \text{CO}_2, \text{H}_2$ and H_2O . K_{E_6} is equilibrium constant for water gas shift reaction.

5.3.2 UCG Control Model

Modeling of underground coal gasification (UCG) plant is crucial for extracting maximum possible efficiency since the entire process is constantly effected from

numerous physical and chemical properties. Considering impossibility or difficulty of acquiring information from sensors since the reactor sits hundreds of meters under the ground, problem of modeling fairly becomes even more complex and difficult. Nevertheless accuracy of the model prediction and ease of control design are at-most key factors to be considered. Highly complex models can offer increase in accuracy, however it results in even more complex control design along with additional expensive investments. Thus, a model is required to predict the chemical composition of product gas against the composition and flow rate of injected gas, coal type, thickness of coal seam and water intrusion [8]. Available models in the literature can be grouped in five types

- Coal Block Models
- Packed Bed Models
- Channels Models
- Process Models
- Miscellaneous UCG Models

Summarized explanation and comparison of these models are presented in [8]. A comprehensive model of a UCG process is comprised of a sub-model for cavity growth, heat and mass transport model and models describing the interaction of process with environment [53]. Hereby, heating value level is one of the prominent parameter prevails among others, which should be kept constantly at its optimum value in the closed loop UCG process control system. The purpose of this research

to find out optimized steam to oxygen ratio constantly to obtain maximum possible output gas product. Appropriate control method should be selected which can cope with complex geometry of coal cavity, highly nonlinear nature of the UCG system, disturbances in situ with providing desired heat value based on approximated design model. Limitations and expected performance of such control algorithm conjure up sliding mode control algorithm, which offers robust and accurate results under disturbances and state variances. Simplified time domain model of UCG is introduced in [1] which can work under different unsteady state model assumptions presented in [69].

Typical UCG plant has two wells for injection air and extracting products gas 25 meters apart from each other as shown 5.1. Injected gases starts chemical reactions with preset ignition system and product gas flow out after subsequent gasification reactions from production well.

The block diagram of simplified model of UCG is illustrated in figure 5.3

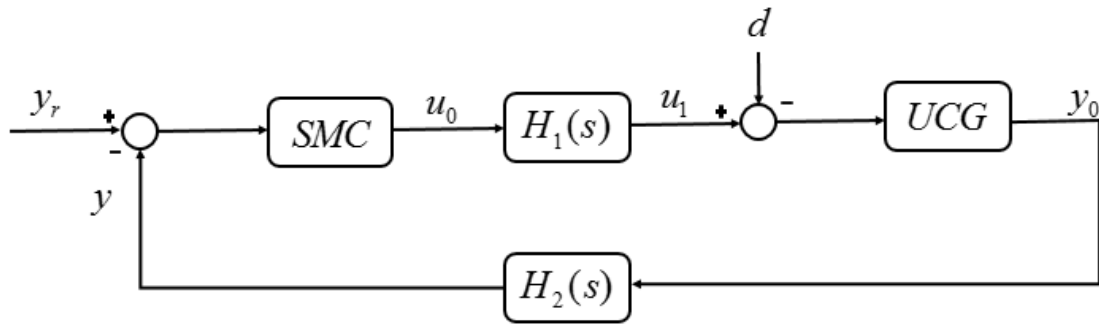


Figure 5.3: UCG Block Diagram

where u_0 is the flow rate of air in $mol/cm^2/s$, y is yielded output gas heating value in KJ/m^3 , y_r is the reference gas output, d is unknown input disturbance of the system with considered boundaries from [4] and [18]. H_1 represents control valve and H_2 refers gas analyzer as first order transfer functions with delays taken from [5].

$$G_1(s) = \frac{\exp(-\tau_{da})s}{\tau_a s + 1} \quad (5.23)$$

$$G_2(s) = \frac{\exp(-\tau_{dg})s}{\tau_g s + 1} \quad (5.24)$$

where τ_a and τ_g are the time constants for G_1 and G_2 . τ_{da} and τ_{dg} are input and output time delays of the system.

Gas analyzer and control valve transfer functions can be ignored for the sake of simplifications in control design along with several mathematical assumptions are addressed just as considered in [5]. The rate of solid density change represented as,

$$\frac{\partial \rho_1}{\partial t} = -M_1 R_1 \quad 0 \leq x \leq L \quad (5.25a)$$

$$\frac{\partial \rho_2}{\partial t} = -M_2 \left[|a_{s1,2}| R_1 - R_2(u) - R_3(u) \right] \quad 0 \leq x \leq L \quad (5.25b)$$

where ρ_1 and ρ_2 refers coal and char. R_1 , R_2 and R_3 are chemical reaction rates for pyrolysis, char oxidation and steam gasification. $a_{s1,2}$ is gas stoichiometric coefficient and M_1 , M_2 are molecular weight of coal and char in g/mol .

The rate of solid temperature change represented in reactor length L is

$$\frac{\partial T_s}{\partial t} = \frac{B \frac{\partial^2 T_s}{\partial x^2} + h(T - T_s) - q_1 R_1 - q_2 R_2(u) - q_3 R_3(u)}{c_{p1} \rho_1 + c_{p2} \rho_2} \quad (5.26)$$

where c_{p1} and c_{p2} are heat capacity of coal and char in unit $cal/g/K$, T_s and T are solid and gas temperatures in Kelvin, h is heat transfer coefficient in $cal/s/K/cm^3$, q_1 and q_2 are reaction heat of coal and char. It is assumed that the input and output gas temperature stays constant.

Pyrolysis and char oxidation reaction rates, R_1 and R_2 , are derived as,

$$R_1 = 5 \frac{\rho_1}{M_1} \exp \left[\frac{-6039}{T_s} \right] \quad (5.27)$$

$$R_2 = \frac{v_g C_7}{u + d} R_{C_2} \quad (5.28)$$

where v_g is gas velocity in cm/s , C_7 is distribution of oxygen concentration in mol/cm^3 as

$$C_7 = 0.21 \frac{u}{v_g} \exp \left[- \frac{a_{7,2}}{u + d} \int_0^x R_{C_2} dx \right] \quad (5.29)$$

where $a_{7,2}$ is stoichiometric coefficient of oxygen, d is input gas disturbance and u is injected input gas flow into UCG reactor which equals to u_0 for simplification.

$$R_{C_2} = \frac{9.55 \times 10^8 \rho_2 P \exp \left[\frac{-22142}{T_s} \right] k_y}{M_2 k_y \sqrt{T_s} + 9.55 \times 10^8 \rho_2 P \exp \left[\frac{-22142}{T_s} \right]} \quad (5.30)$$

where k_y is mass transfer coefficient in $mol/cm^3/s$, P is reactor pressure in atm .

Steam gasification reaction rate is

$$R_3 = \frac{d}{d+u} R_{C_3} \quad (5.31)$$

where

$$R_{C_3} = \frac{k_y P^2 \rho_2 E_1}{P^2 E_1 \rho_2 + k_y M_2 (P + E_2)^2} \quad (5.32)$$

where E_1 and E_2 are

$$E_1 = \exp \left[5.052 - \frac{12908}{T_s} \right] \quad (5.33)$$

$$E_2 = \exp \left[-22.216 + \frac{24880}{T_s} \right] \quad (5.34)$$

The production well gas output, y is derived as,

$$y = \frac{100 \left[\alpha \int_0^L R_1 dx + \beta \int_0^L R_3 dx \right]}{\gamma \int_0^L R_1 dx + \nu \int_0^L R_3 dx + \zeta \int_0^L R_2 dx + 0.79 \frac{u}{v_g}} \quad (5.35)$$

where

$$\alpha = \frac{1}{v_g} \left[a_{11} H_1 + a_{31} H_3 + a_{51} H_5 + a_{81} H_8 \right] \quad (5.36)$$

$$\beta = \frac{1}{v_g} \left[a_{13} H_1 + a_{33} H_3 \right] \quad (5.37)$$

$$\gamma = \frac{1}{v_g} \left[a_{11} + a_{21} + a_{31} + a_{51} + a_{81} \right] \quad (5.38)$$

$$\nu = \frac{1}{v_g} \left[a_{13} + a_{33} \right] \quad (5.39)$$

$$\zeta = \frac{a_{2,2}}{v_g} \quad (5.40)$$

5.4 Steady State and Existence of Extremum

The change rate of coal density and hence the coal pyrolysis reaction is zero under the steady state condition. This simplifies the output equation 5.35 of the UCG process to the following form with disregarded constants,

$$h = \frac{\int_0^L R_3 dx}{\int_0^L R_2 dx + \int_0^L R_3 dx + G} \quad (5.41)$$

which leads to the following conditions. G is the output gas product in $moles/cm^2/s$.

$$\begin{aligned} h &\propto R_3 \\ h &\propto \frac{1}{R_2} \end{aligned} \quad (5.42)$$

This is also elaborated in Fig. 5.4.

The expression for steady state solid temperature (T_s), by letting the total time derivative equated to zero, is given below:

$$T_s(x) = q_2 \int_0^L \int_0^L R_2 dx dx - q_3 \int_0^L \int_0^L R_3 dx dx \quad (5.43)$$

The fact that char oxidation reaction (R_2) is exothermic in nature while the steam gasification reaction (R_3) is endothermic and that heat of reaction of R_2 is much greater than that of R_3 i.e., $q_2 \gg q_3$, justifies the following proportionality.

$$T_s(x) \propto R_2$$

$$T_s(x) \propto R_3$$

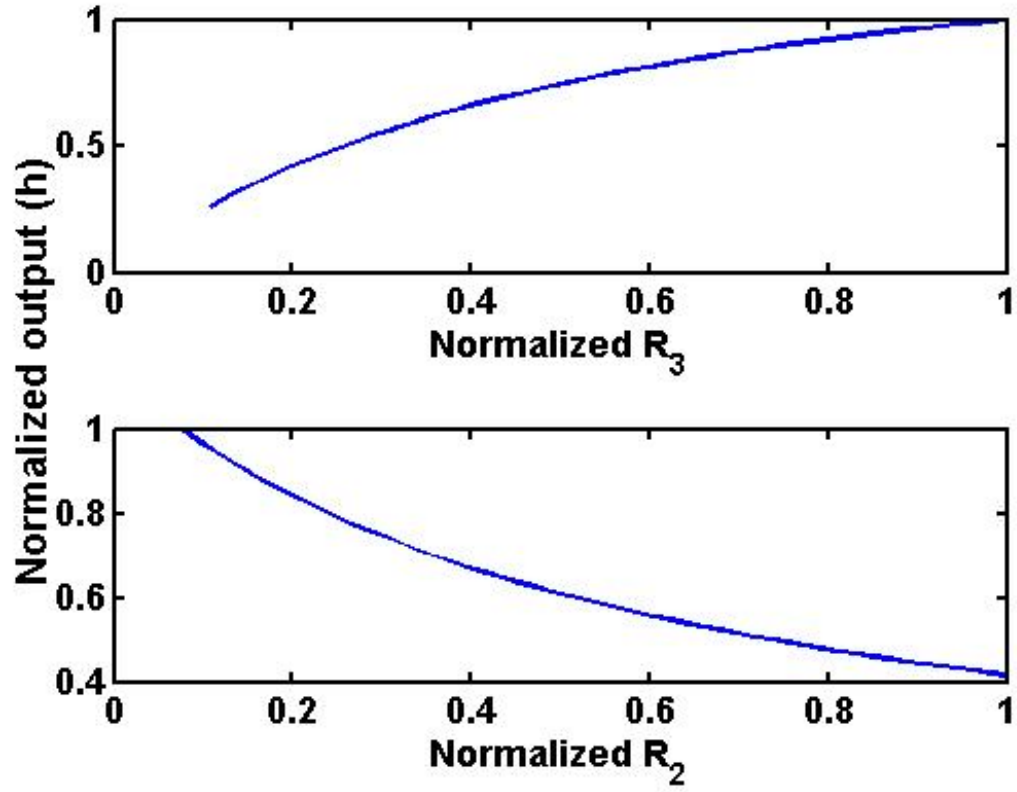


Figure 5.4: Change of R_2 and R_3 on h .

Moreover, the char oxidation reaction R_2 5.28 is rephrased as,

$$R_2 = \eta_2 R_{c2}$$

where $0 < R_{c2} < 1$ 5.30, $\eta_2 = a/(1 + a\lambda)$ and $a = 0.21$. This establishes the following proportionality. λ is defined as steam to oxygen gas ratio.

$$\begin{aligned}
\eta_2 &\propto \frac{1}{\lambda} \implies R_2 \propto \frac{1}{\lambda} \\
R_{c2} &\propto T_s(x) \implies R_2 \propto T_s(x)
\end{aligned} \tag{5.44}$$

Similarly for the steam gasification reaction, R_3 5.32, the following inequalities hold true.

$$\begin{aligned}
R_3 &\propto \lambda \\
R_3 &\propto T_s(x)
\end{aligned}$$

Now following the expressions in (5.44) and (5.44). Actually access amount of water (steam) extinguishes the process, then following proportionality is straight forward.

$$T_s(x) \propto \frac{1}{\lambda}$$

Thus based on the above established proportionality the expressions for R_i s and $T_s(x)$ can be written as,

$$\begin{aligned}
R_{c2} &= \frac{c_2}{\lambda} \implies R_2 = \eta_2 \frac{c_2}{\lambda} \\
R_{c3} &= \frac{c_3}{\lambda} \implies R_3 = \eta_3 \frac{c_3}{\lambda} \\
T_s(x) &= \frac{T_c}{\lambda}
\end{aligned} \tag{5.45}$$

where c_2 , c_3 and T_c are the constants of proportionality. Hence the output equation with disregarding constants can be rewritten as,

$$h = \frac{ac_3L\lambda}{ac_2L + ac_3L\lambda + G\lambda(1 + a\lambda)} \quad (5.46)$$

Now, for extremum check, differentiating with respect to λ ,

$$\begin{aligned} \frac{dh}{d\lambda} &= 0 \\ 0 &= (aL)^2c_2c_3 - a^2Lc_3G\lambda^2 \end{aligned} \quad (5.47)$$

implies that

$$\lambda = \pm \sqrt{\frac{c_2L}{G}}.$$

Since λ can not be negative hence the extremum (maxima) exist for (5.41) with $\lambda = \sqrt{\frac{c_2L}{G}}$. The variation in output is depicted in Figure 5.5

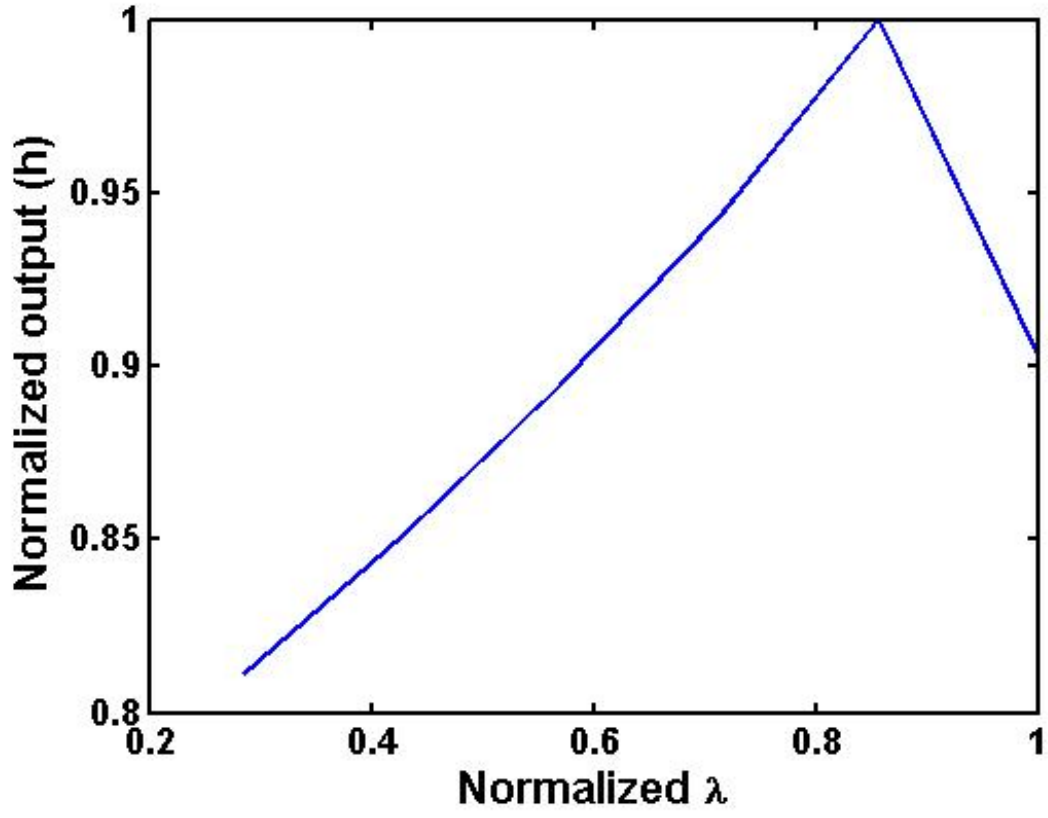


Figure 5.5: Description of maximum output with respect to λ for a fixed G .

5.5 Simulation Results

Sliding mode control system offers robust and accurate tracking performance against modeling inaccuracies and input disturbances. SMC is implemented in [8] with using presented UCG reactor model, dynamics of control valve and gas analyzer in [4] with using Matlab simulation.

The air flow rate u_0 consists of oxygen and steam. The concentration of O_2 and steam determine temperature of the reactor and directly affects the output of plant. Even though steam does not participate in any chemical reactions, increase in oxygen rate inflates reactor temperature through char oxidation reaction, but also creates higher rate of carbon dioxide which greatly decreases the heating value of the reactor. This section presents simulation results of finding maximum possible oxygen rate of given model.

In actual plant, steam is not provided into the reactor, but significant amount of steam is required for steam gasification reaction that produces CO and H_2 . Necessary steam for the is acquired from near by surrounding aquifers. The amount of steam can be controlled by controlling the reactor pressure P , however the exact amount of steam cannot be known due to absence of sensors. Nevertheless, upper and lower limits of performable reactor steam values are known. When steam exceeds the upper limit, cavity is flooded and heat value decreases substantially.

The performed simulations showed that when the rate of oxygen reaches the vicinity of its extremum value, UCG plant absolute capacity is also overtaken and process is collapsed due to the excessive amount of steam. Thus, sliding mode based self-optimization algorithm is truncated based on the cavity pressure P .

The inlet pressure is modeled depending on the steam requirement with given expression in 5.48

$$P(x = 0) = \frac{\lambda(t)}{\delta} \text{sign} \left[\lambda(t) - \lambda(t - 1) \right] \quad (5.48)$$

where $x = 0$ is the position of inlet well, $\lambda(t)$ is required steam to oxygen ratio and $\lambda(t - 1)$ is the steam to oxygen ratio at the previous time instant. The variable δ can be chosen as its value provide a trade-off between the maximum achievable output and the load on input compressors.

Self-optimization search procedure is stopped based on the value δ when $P = 5atm$. Figure 5.6 shows the monotonously increasing reference input g is tracked by UCG process output y with given constant temperature. Reference input g is constant after 450 seconds where it is subjected to a constraint on the inlet pressure of the UCG process when the input flow rate , oxygen O_2 and nitrogen N_2 , is $G = 2 \times 10^{-4}$.

Figure 5.7 shows the corresponding steam to oxygen ratio produced by the optimization algorithm.

Figure 5.8 and 5.9 show the monotonously increasing reference input g and output y and the corresponding steam to oxygen ratio for the case when $G = 2.5 \times 10^{-4}$.

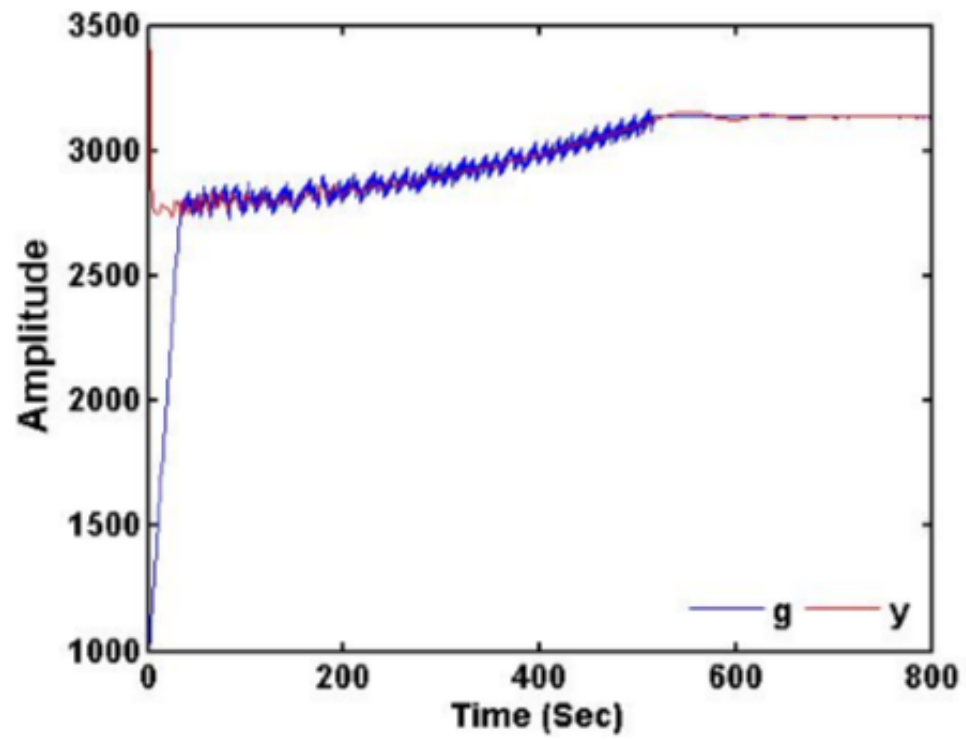


Figure 5.6: Reference Input and Process Output while $G = 2 \times 10^{-4}$

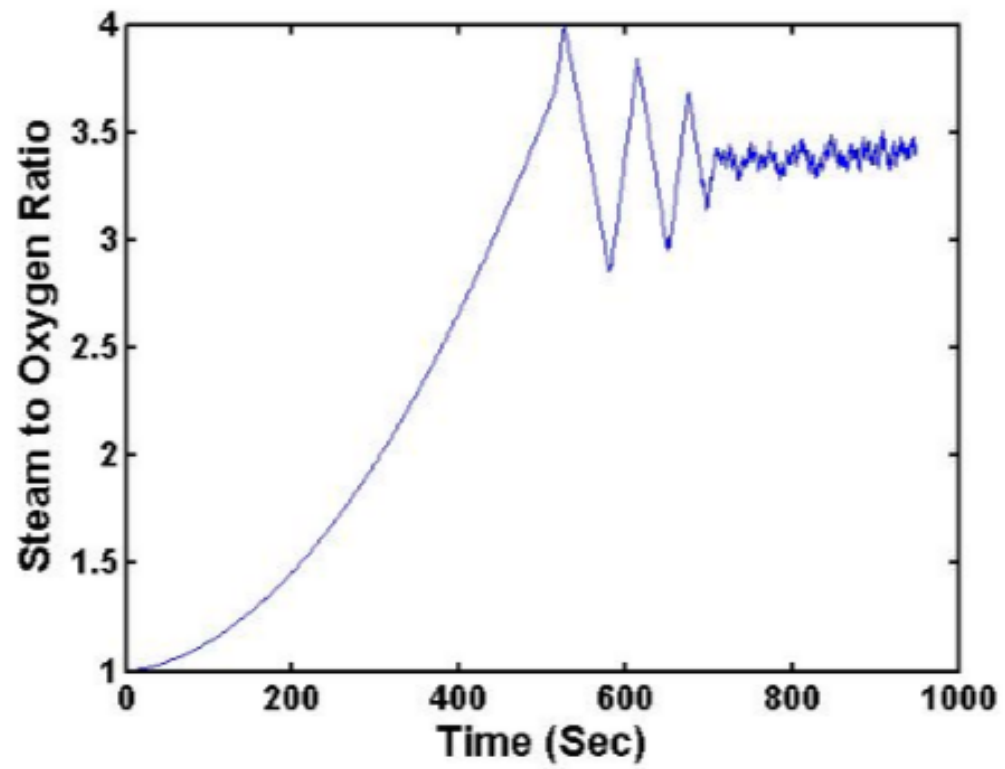


Figure 5.7: Steam to Oxygen Ratio while $G = 2 \times 10^{-4}$

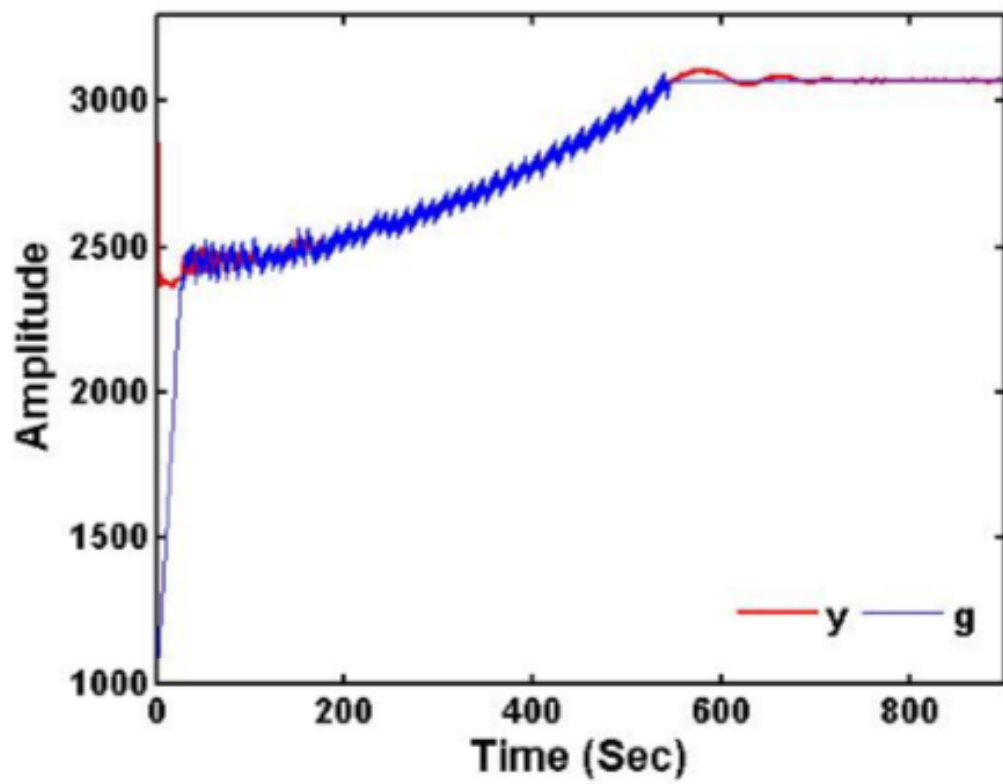


Figure 5.8: Reference Input and Process Output while $G = 2.5 \times 10^{-4}$

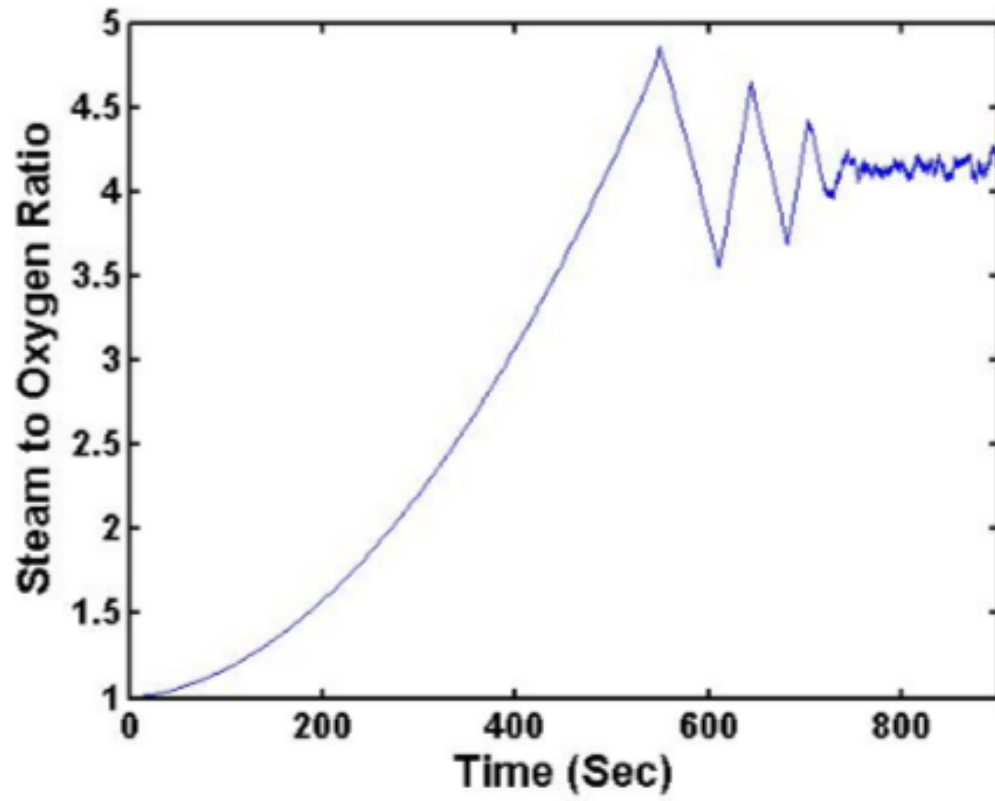


Figure 5.9: Steam to Oxygen Ratio while $G = 2.5 \times 10^{-4}$

Chapter 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this research self-optimization search is studied in the frame of sliding mode control systems. Sliding mode control methodology (SMC) is an efficient technique in terms of high dynamic performance, accuracy, robustness and convenience of solving very diverse nonlinear control problems involved with external disturbances and uncertainties. Sliding Mode (SM) self-optimization procedure implies that output tracks monotonously decreasing reference input. As a result, the output value reaches the minimum or maximum point.

The idea of self-optimization for controlling system with time varying gain is studied in the previous works, even more, it was used in many applications. Published studies [57], [34] remarked accuracy of the method based on sliding mode existence conditions. Thus accuracy was found inadequate and several complicated modifications are introduced. However these complex methods are based on changing the rate of decaying reference input. These complicated methods increased accuracy but

searching process takes more time. It is shown that the potential of algorithm was not properly utilized full extent. This research is oriented towards the system motion after sliding mode disappears. It is proved that constant rate of reference input model is faster and better then suggested complex models. Even if complicated modified methods can be faster for some small initial condition, but for high enough initial conditions existing model is faster and accurate.

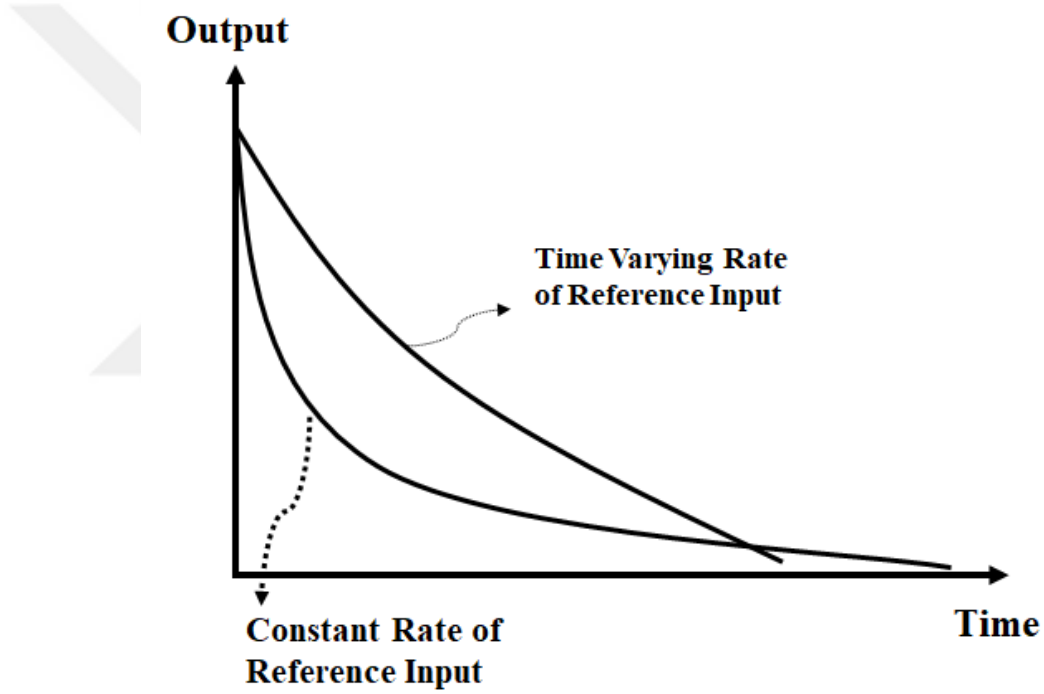


Figure 6.1: Comparison of Model Search Speed

The constant rate of reference input was analyzed previously in chapter 2 and accuracy of the model was estimated. Our analysis shows that without any changes, the model accuracy is higher than before and it is determined by the width

of hysteresis loop, in which periodic oscillations occurs in the system. If model is modified, SM exists in the beginning of search to minimum point, but the model accuracy remains same. As to rate of convergence, in some area the first model defined in chapter 2 is faster than modified model, but after some point, the modified model is faster 6.1.

The control of electric power is one of the most attractive area of the sliding mode control system, because the basic element of power system is converters which can only operate via on-off mode. Hence, control is discontinuous by nature of the plant, where this discontinuities is used to enforce sliding mode. Sliding mode control (SMC) methodology can be used to control switching frequency of a DC/AC inverter implemented to three phase load. Meanwhile, it should be noted that chattering is the main obstacle to application of SMC on power converters because it leads heat losses. Besides, designer should not surrender for claiming higher accuracy while obtaining low chattering level. Thus, the two problems are handled in this research. The first one is minimizing the switching frequency for a given hysteresis loop of switching devices. The second problem is minimizing the hysteresis loop which would let us improve the system accuracy without exceeding admissible switching frequency value.

The method for minimizing switching frequency for presented width of the hysteresis loop is developed. It results in minimizing heat losses in the power converter. On the other hand, the system accuracy can be improved by minimizing the width of hysteresis loop with keeping the switching frequency at the admissible level.

The movement of microscopic particles cause out-of-focus images and observation becomes impossible. Thus, microscopes needs special control algorithms

which has three dimensional spacial tracking. Sufficient lateral particle positioning is ensured with various methods but they require efficient axial tracking techniques. In this research capability enhancement of Electrically Tunable Lens (ETL) is studied in the frame of self-optimization sliding mode control. A sharpness metric function which has quadratic relationship with difference between particle position and focal plane is selected to be maximized.

Conventional methodology implies inserting integral to system which increases the order of model by one, hence sliding mode cannot exist in principle. Entire system is used as an integrator in presented methodology which is based on tracking system. This advantage is used by replacing integrator with first order system block and extremum point is found.

Three dimensional particle tracking simulation with triangular disturbance is successfully performed in discrete time. Sampling-time of the microscope determined accuracy of the algorithm, which cannot be selected less, since width of hysteresis must be larger than chattering amplitude. The most prominent advantage of used technique is that offered self-optimization algorithm does not need any calibration for different models, which makes it universally applicable for any amount of range.

Underground coal gasification (UCG) process control models should provide maximum possible output gas flow with maintaining desired constant heat value under the external disturbances and internal model inaccuracies. System consists of high order complex equations with complicated reactor geometry. The output gas flow is directly related to unknown oxygen-steam ratio function, hence this problem is approached by the virtue of sliding mode self-optimization tracking technique. Zero

order dynamics stability analyses are performed previously [8], thus recommended model is considered in this study.

The output gas flow can be maximized by changing oxygen-steam ratio and existence of an extremum point is proven which has be reached. Besides, boundary of pressure with oxygen-steam ratio is discovered and simulations are performed with considering such modification on the recommended model. Simulation results confirm successful tracking and output gas flow is maximized with finding distinct optimal oxygen-steam ratio.

6.2 Future Work

Thesis is oriented on self-optimization methodologies and applications in the frame of sliding mode control technique. Self-optimization consists in finding a combination of input parameters such that the scalar output of the plant attains its extremal value.

6.2.1 Experimentation Frequency Control of DC/AC Inverters

The dependence between frequency and voltage of neutral point V_N is found and used for minimizing the sum of switching frequency results in reduction of power converter heat losses in Chapter 3. Aforementioned theory is proved analytically and developed algorithm simulated. It is difficult to measure the local frequency, since it

is flowing in the state and induction motor is not a static load. Thus, calculation of reduced frequency may be possible with applying equivalent control method. If the sum of switching frequency is lower than admissible value, the hysteresis width can be decreased for increasing accuracy. These results should be validated by experiments. The objective is finding results as exactly formulated in the theory. When anticipated results endorses analytical and simulated findings, it is planned to be published in one of the international journal.

6.2.2 Minimization of Heat Losses in Induction Motors

Minimization of heat losses in the induction motor can be performed as a future work. Usually the control of induction motor advises selection of flux and a mechanical variable to be controlled, for instance, speed. Different kinds of speed control methods are classified in the literature. Nevertheless, heat losses stands along as a required to be developed problem on future work of the researchers. Conventional control methods of the induction motors can be listed as,

- Stator voltage control
- Rotor voltage control
- Volts Hertz Control
- Frequency control

On the other hand, another way of decreasing heat losses is investigated. Self-optimization methods can be used to change a reference input in flux such that heat losses are minimized in the induction motors. Load current is created by required flux and produces the desired torque. But if the induction motor runs at constant

low torque needed operation, the created flux will be close to saturation which is not certainly desired. The induction motor heat losses is directly related to load current square.

$$P_{loss} = 3I_r^2 R_r + 3I_s^2 R_s \quad (6.1)$$

where I_r , I_s and R_r , R_s are stator and rotor currents and resistance. 25% – 40% loss of power appears in stator where this rate is 15% – 25% for rotor. Thus, naturally, the optimization criteria will be minimization of heat losses. It is believed that the load current can be decreased with providing required torque and speed values. If flux can be reduced with a given constant torque amount, the load current could be minimized with along the reduced heat losses in steady state operations. On the other hand, if flux value is too low, high current value is needed to produce desired torque value, which increases heat losses. Under the consideration of steady state period, we can calculate the heat losses with estimated load current. The control input for flux has not been found yet, but a reference input for flux should exist such that heat losses are minimized, which makes it reasonable to apply self-optimization procedure. Because, required minimum flux value corresponding to the minimum value of losses is unknown. Aforementioned procedure is explained in Chapter 2. The optimization procedures, [30], apply some undesirable additional signal for induction motors. However, our proposed procedure does not require any kind of gradient information.

6.2.3 Maximization of Friction Torque on ABS Systems

In the third part of the future work, it is planned to apply presented self-optimization control method on the anti-lock braking systems. Anti-lock Braking System (ABS) is widely used as important tool for automobiles, which makes cars can stop faster and turns safely without locking the wheels. If wheels are locked, steering will stop immediately and slipping starts which causes control loss of the car and possible accident. The principle of ABS is oriented on creating optimum friction by measuring wheel's angular velocity and possible linear acceleration without locking the wheels.

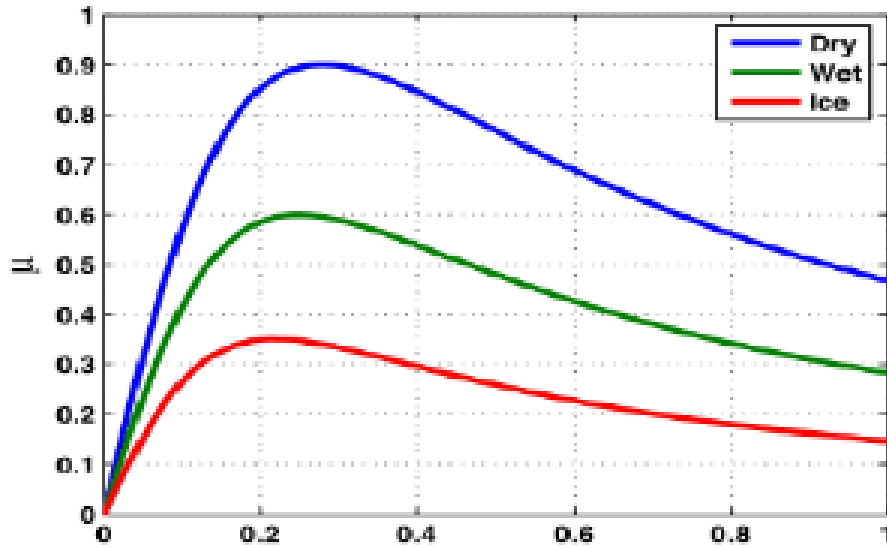


Figure 6.2: Friction Torque versus Road Condition [41]

Maximum friction torque appears for some unknown value of slip, which depends on driving condition and state of road. These conditions are unknown and changing, but only the need of maximum torque is known. Variable change of gain, uncertainty in the braking system and nonlinear nature of the system make ABS as a good candidate for our self-optimization methodology. As it is pointed out in Chapter 2, the conventional approach to self-optimization is based on calculation of gradient or evaluation of any gradient information. However, Sliding Mode (SM) self-optimization procedure implies that output tracks monotonously decreasing or increasing reference input, reaches extremum point without requiring any information of the gradient. Thus, we are planning to analyze behavior of the system and find the optimum selected reference input such that friction torque is maximized.

6.2.4 3-Dimensional MPPT Control of PV Systems

Sliding mode self-optimization procedure can be applied for PV systems to maximize the output power. It usually have a self-optimization system provides maximum power with fixed stationary position of the panel platform. In the course of varying environment, maximum point can be reached with changing position of the PV element.

Constant motion of the Sun, reflection of sunlight and shading of clouds change maximum power point (MPP) of the PV system. Even if measuring position of Sun is applied, MPP will be missed considerably, in which it is intended in the scope

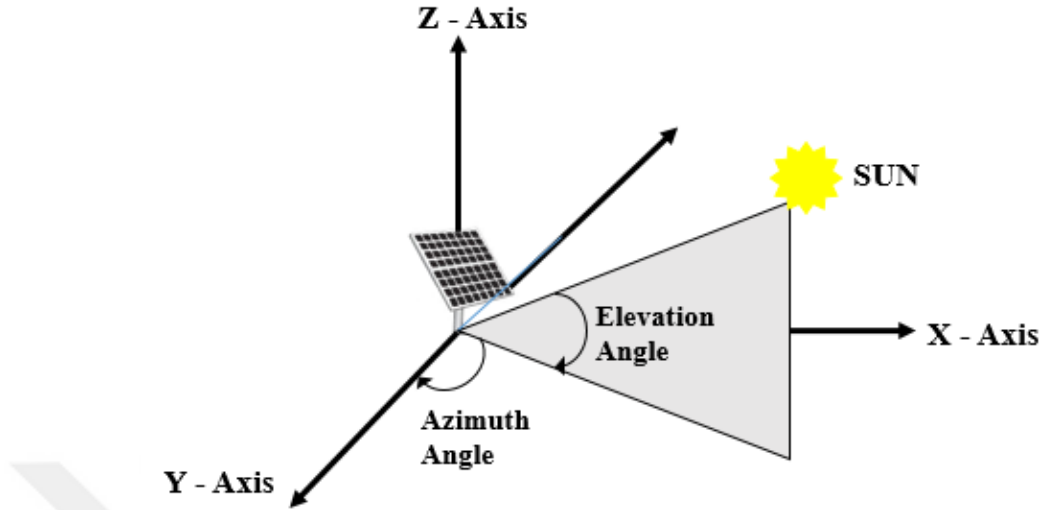


Figure 6.3: Three Dimensional Tracking

of our study. Thus, it leaves us pretty difficult optimization problem with respect to solve, because gradient is a vector now, and makes problem much more complicated.

We have two new parameters, which are the angles of Sun's position. It is desired to solve this complex problem with changing position of the Pv panel with servomotors. It would be interesting to have three dimensional optimization to find maximum power depending of not only on the duty cycle of the power converter but also positions of the platform. This could increase efficiency considerably. The orientation of this study is to prove maximizing the generated power analytically and via simulations with maximum possible accuracy.

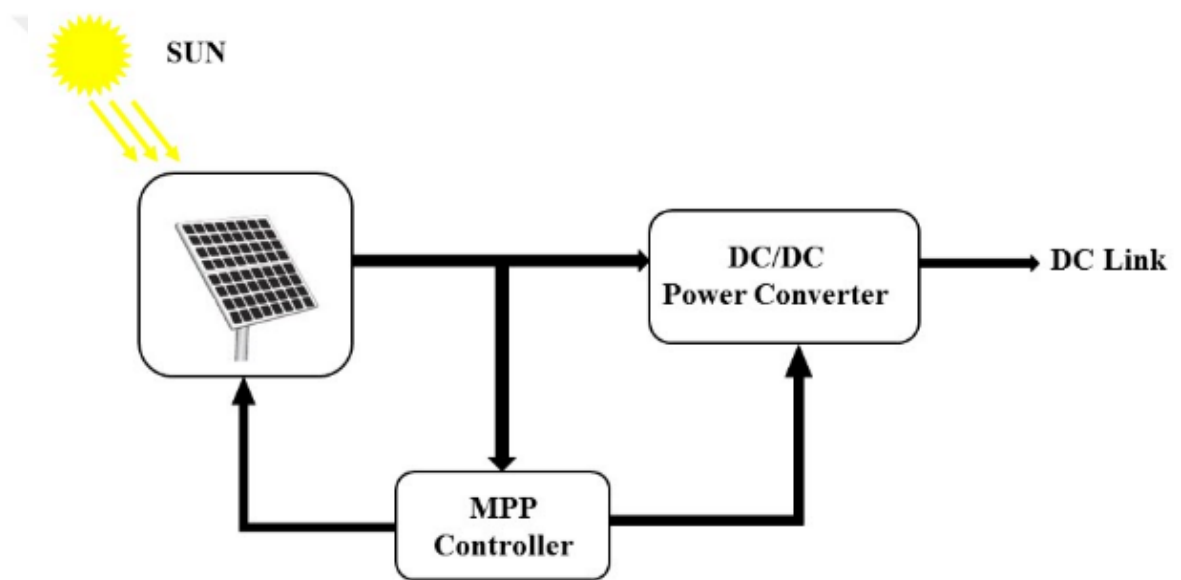


Figure 6.4: Control Schematics

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