SIMULATION OF AC-DC CONVERTER FOR DC MOTOR APPLICATION USING FUZZY LOGIC CONTROL

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This project report presented in partial
fulfillment of the requirements for the award of
the Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
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JUNE, 2013

ABSTRACT

The AC to DC variable converter becomes an important drive configuration for DC motor applications across a wide range of powers and speeds. Consequently, this converter requires a controller with a high degree of dynamic response. Generally, Proportional-Integral- Differential (PID) controllers have been applied to the converters because of their simplicity. However, PID controller is unable to adapt and approach the best performance when applied to nonlinear system. This problem is solved by the intelligence of the Fuzzy Logic Controller (FLC). Therefore, in this project, simulation of a single phase AC-DC converter is designed to convert AC voltage to variable DC voltage to drive DC motor application with the FLC. In order to obtain the desired speed of dc motor, the FLC is employed to control the firing angle of the power converter. The controller is designed to stabilize the output voltage of AC-DC converter. To verify the effectiveness of the proposed method, both of the FLC and the PID controllers have designed and compared in term of settling time and overshoot. In this project, MATLAB/SIMULINK power system toolbox is used to simulate the proposed system. The simulation result show that the amplitude of output voltage of the DC-AC converter and motor speed can be controlled. Meanwhile, Fuzzy logic controller uses DC motor speed as feedback enhances the system performance by significantly improving the dynamic performance of the AC-DC converter. The simulation results on the real control system reveal that the proposed FLC is able to overcome the disadvantages of conventional PID controller.

ABSTRAK

Pengubah AC/DC berubah-ubah menjadi konfigurasi pacuan penting untuk aplikasi DC motor dalam pelbagai kuasa dan kelajuan. Oleh itu, pengubah ini memerlukan sebuah alat pengawal yang mempunyai tahap tindak balas dinamik yang tinggi. Secara umumnya, *Proportional-Integral- Differential (PID)* telah biasa digunakan kepada pengubah kerana ianya mudah untuk dikawal. Walau bagaimanapun, pengawal PID adalah tidak boleh dilaraskan dan susah untuk mencapai prestasi terbaik apabila diaplikasikan di dalam sistem tak linear. Masalah ini boleh diatasi dengan menggunakan kepakaran Pengawal Logik Kabur (FLC).Oleh itu, dalam projek ini, simulasi satu fasa pengubah AC-DC direka untuk menukarkan AC voltan kepada pembolehubah DC voltan dan diaplikasikan pacuan DC motor dengan FLC tersebut. Dalam usaha untuk mendapatkan kelajuan yang dikehendaki oleh DC motor, FLC yang digunakan sebagai mengawal sudut menembak bagi pengubah kuasa. Pengawal ini direka untuk menstabilkan voltan keluaran dari pengubah AC-DC. Untuk memastikan keberkesanan kaedah yang dicadangkan itu, kedua-dua jenis pengawal FLC dan pengawal PID telah direka dan dibandingkan dari segi masa penyelesaian dan masa lajakan. Dalam projek ini, MATLAB / SIMULINK sistem kuasa peralatan digunakan untuk mensimulasikan sistem yang dicadangkan. Hasil simulasi menunjukkan amplitud voltan output pengubah DC-AC dan kelajuan motor boleh dikawal. Sementara itu, pengawal logik kabur(FLC) menggunakan kelajuan DC motor sebagai maklum balas untuk meningkatkan prestasi dinamik pengubah AC-DC. Keputusan simulasi di sistem kawalan sebenar menunjukkan bahawa pengawal FLC yang dicadangkan dapat mengatasi keburukan konvensional pengawal PID.

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LIST OF SYMBOLS AND ABBREVIATIONS

α	-	firing angle
ω	-	Angular speed
I_a	-	Armature current
I_F	-	Field current
R_A	-	Armature resistance
L_A	-	Armature Inductance
K_e	-	Electric motor constant
µe	-	degree of membership function of error
e	-	error
Δe	-	of membership function of delta of error
che	-	Change of error
FLC	-	Fuzzy logic controller
MF	-	Membership function
P	-	Positive
Z	-	Zero
PS	-	Positive small
PM	-	Positive medium
PB	-	Positive big
N	-	Negative
PID	-	Proportional-Integral- Differential

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CHAPTER 1

INTRODUCTION

1.1 Project Background

The ac to dc converter is an integral part of any power supply unit used in the all electronic equipments. And can be used as an interface between utility and most of the power electronic equipments. These electronic equipments form a major part of load on the utility. Generally, to convert line frequency ac to dc, a line frequency diode bridge rectifier is used. And sometimes a large filter capacitor is used To reduce the ripple in the dc output voltage [1].

And the AC-DC converters serve as rectifiers. They convert ac to dc in a number of industrial, domestic, agricultural, and other applications. Rectifiers are used as stand-alone units feeding signal and multiple dc motor and as input stages of ac drives because of their virtually unlimited output power and fine controllability. Their response is usually adequate to handle electromechanical transient occurring in drives.

AC-DC line-commutated converters or, as they also called, converters with natural commutation or passive rectifiers, are the most usual choice for applications, where a single-phase and three-phase supply is available. This is due to simplicity of the circuit requiring a minimum number of active and passive components. Thyristors are the line-commutated power switches. The term (line-commutated) describes the type of commutation, i.e. the transfer of current from one conducting element to the next, as a function of the mains voltage. To turn on the thyristor , an injection of current pulse into its gate is required [14].

1.2 Problem Statements

Traditionally DC motors were controlled using PID method. However this method generates high overshoot and long settling time.

In order to improve performance of the DC motor drive system a FLC will be proposed. By this reason, the problem statement of this project is how to develop FLC model to apply in DC motor drive. Hence the performance of the speed controller can be improved.

1.3 Project Objectives

The major objectives of this proposal are:

i) To model a regulated AC-DC converter fed DC motor without controller (open loop) and simulate using MATLAB Simulink.
ii) To simulate Proportional-Integral-Derivative (PID) Controllers to control the regulated AC-DC converter to drive dc motor.
iii) To design model fuzzy logic controller (FLC) to control the regulated AC-DC converter to drive dc motor.

1.4 SCOPE OF PROJECT

This project is primarily concerned with development of regulated AC- DC converter to drive DC motor and control its speed by using Triangle fuzzy logic controller with MATLAB Simulink software. The scope of proposed fuzzy logic controller is limited Triangle as a proposed controller. The analysis covered the output voltage of the regulated AC-DC converter and the step response of the DC motor speed based on reading on overshoot ratio, rise time, peak time and settling time.

1.5 Project report layout

This project report is organized as follows;

Chapter 1 briefs the overall background of the study. A quick glimpse of study touched in first sub-topic. The heart of study such as problem statement, project objective, project scope and project report layout is present well through this chapter.

Chapter 2 covers the literature review of previous case study of types of AC-DC converters and based on fuzzy logic controller background to control DC motor and development. Besides, also Proportional-Integral-Derivative (PID) Controllers, general information about AC-DC Converter and theoretical revision on fuzzy logic control system also described in this chapter.

Chapter 3 presents the methodology used to design open loop AC-DC Converter feeds DC motor and also closed loop with fuzzy logic controller and Proportional-Integral-Derivative (PID) controllers to drive DC motor. All the components that have been used in designing of fuzzy logic controller are described well in this chapter.

Chapter 4 reports and discuss on the results obtained based on the problem statements as mentioned in the first chapter. The simulation results from PID controller and the proposed of fuzzy logic controller will be analyzed.

Chapter 5 will go through about the conclusion and recommendation for future study. References cited and supporting appendices are given at the end of this project report.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review about this project has been made from various sources like journals, books, articles and others. From the literature review, the input that has been collected is useful for better understanding of this project.

S. baskar P.Subbaraj N.M. prakash kumar

Fuzzy Logic and Neural Network concepts are applied to DC drive system. A systematic approach to construct, membership functions of FLC using Shrinking Span Membership Functions (SSMFs), is adopted here [3]. This paper proposes a SSMFs Fuzzy Logic Controller for Current and Speed control loops of DC Drive systems. The digital simulation study of model system is carried out with proposed PI controllers using MATLAB-SIMULINk software.

Simulation result shows the superiority of proposed controller over fixed parameter PI controller and best possible FLC can be designed without expert knowledge and extensive tuning of parameters. The proposed method reduces the design time of Fuzzy Controller from down to earth.

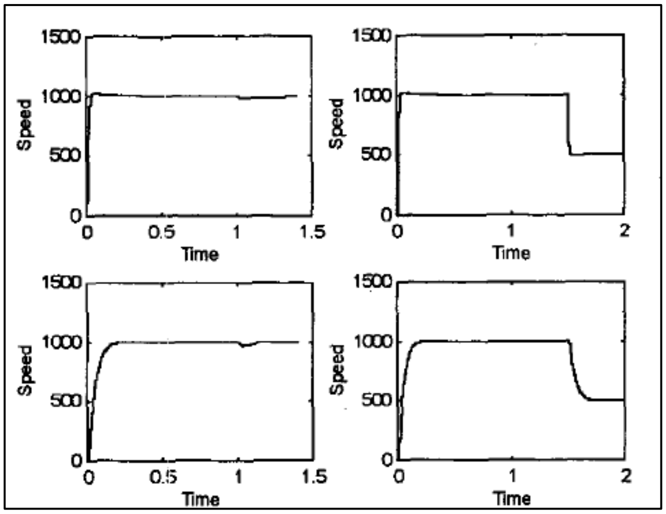


Figure 2.1: Simulation result

Jong-Bae Lee, Tae-Bin Im, Ha-Kyong Sung , Young-Ouk Kim

In this paper, focuses on a low cost speed control system using a fuzzy logic controller for a Brushless DC Motor was explained by [4]. In a digital controller of brushless DC Motor, the control accuracy is of a high level, and it has a fast response time. they used a hall IC signal for the permanent magnet rotor position and for the speed feedback signals, and also for a microcontroller of 8-bit type (80CL580); also designe the fuzzy logic controller and implemented the speed control system of brushless DC Motor. To acquire an accurate fuzzy logic control algorithm, a simulation with the MATLAB program has been made, while the performance of the system, done with an experiment for a unit step response, was also verified.

Mohamed. A. Enany

Description a MATLAB/Simulink realization of the DC motor speed control method by controlling the voltage applied to the armature circuit using single phase AC-DC converter drive[7]. A comparison between the application of single phase semi converter and single phase full converter is presented. Torque-speed characteristics are obtained for different values of firing angle to demonstrate its effect on the linearity of the characteristic.

2.2 Rectifier converter

Rectifier circuits have been the most common power electronics circuits used to convert AC to DC. The AC-DC converter produces a DC output from an AC input while the average power transferred from an AC source to a DC load. This converter usually also called as a rectifier. The word rectification is used not because these circuits produce DC but rather because the current flows in one direction. Generally, there are two types of AC-DC converters which are uncontrolled and controlled. The input of these converters can be single phase or multi-phase (3 phase).

2.2.1 Uncontrolled Single Phase Rectifier

This type of rectifier consists of half-wave rectification and full-wave rectification. Uncontrolled rectifiers make use of diodes. Diodes are two-terminal semiconductor devices that allow flow of current in only one direction. The two terminals of a diode are known as the anode and the cathode. The designs are cheap and popular in the industrial applications. In some of these rectifiers, the AC source from the electric utility is directly rectified without using of an expensive and bulky transformer. In some applications, the DC voltage from the rectifier is connected to a DC bus for distribution to several different circuit systems, subsystems and other converters as loads [2]. In other applications, the rectifiers also supply power to inductive-resistive (motors) and capacitive-resistive (power supplies) loads.

i) Single Phase Half-Wave Rectifiers

The simplest of the rectifier circuit is a single phase half-wave rectifier consists of a single diode as shown in Figure 2.2. A diode is the simplest electronic switch. It is uncontrolled in that the on and off conditions are determined by voltages and currents in the circuit. By using diode, the DC level of the output and the power transferred to the load are fixed when the source and load parameters are established. It produces an output waveform that is half of the incoming AC voltage waveform Figure 2.3. The positive pulse output waveform occurs because of the forward-biased condition of the diode. A diode experiences a forward-biased condition when its anode is at a higher potential than its cathode. Reverse bias occurs when its anode is lower than its cathode. During the positive portion of the input waveform, the diode becomes forward biased, which allows current to pass through the diode from anode to cathode, such that it flows through the load to produce a positive output pulse waveform. Over the negative portion of the input waveform, the diode is reverse-biased ideally so no current flows. Thus, the output waveform is zero or nearly zero during this portion of the input waveform.

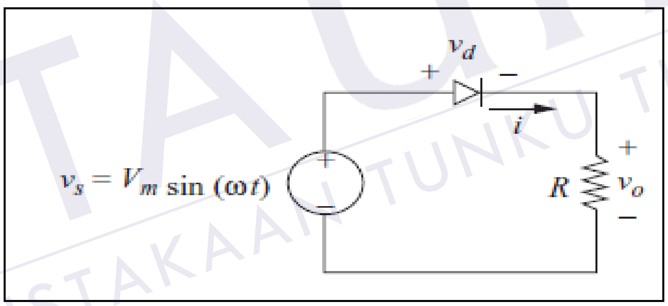


Figure 2.2: Single phase half-wave rectifier.

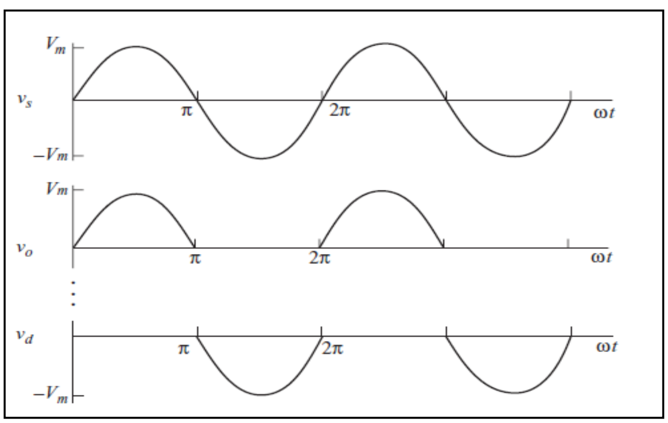


Figure 2.3: Voltage waveform.

ii) Single Phase Full-Wave Rectifiers

The objective of a full-wave rectifier is to produce a voltage or current that is purely dc or has some specified dc component. While the purpose of the fullwave rectifier is basically the same as that of the half-wave rectifier, full-wave rectifiers have some fundamental advantages. The average current in the ac source is zero in the full-wave rectifier, thus avoiding problems associated with nonzero average source currents, particularly in transformers. The output of the full-wave rectifier has inherently less ripple than the half-wave rectifier. [2]

There are two types of full-wave rectifiers that are the bridge rectifier and the center-tapped rectifier as shown in Figure 2.4 and Figure 2.5.

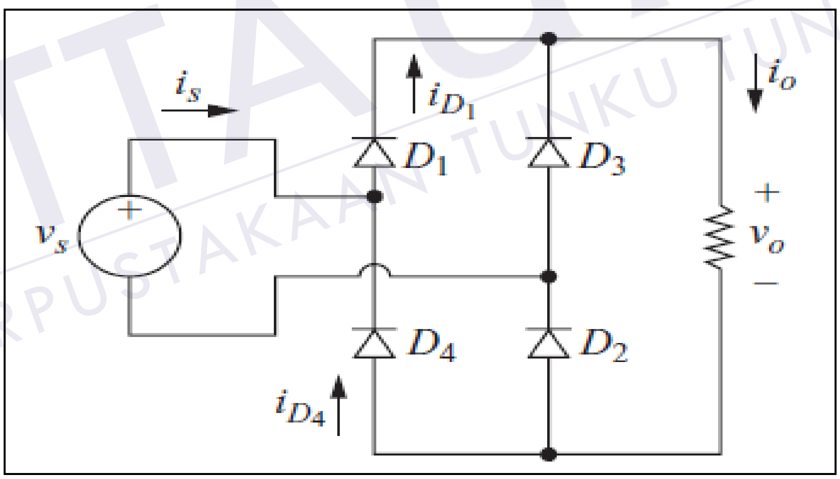


Figure 2.4: The bridge rectifier

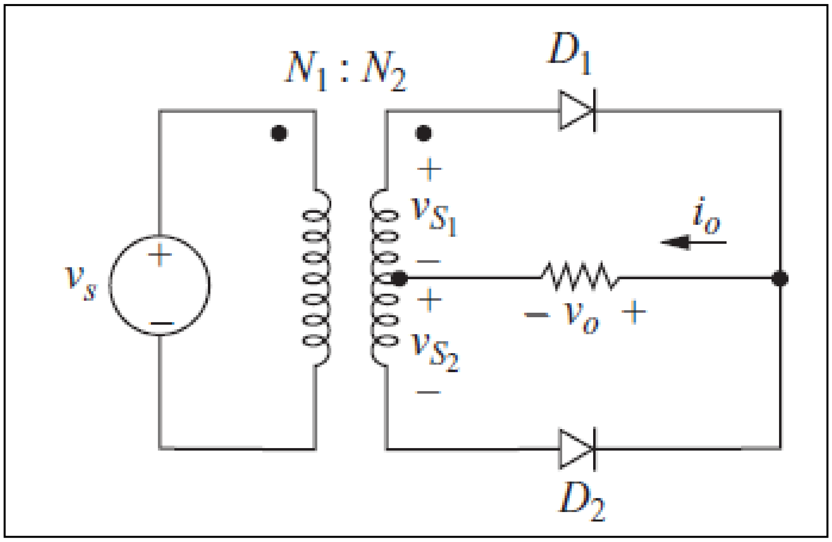


Figure 2.5: The centre-tapped transformer rectifier

The lower peak diode voltage in the bridge rectifier which consists of four diodes arranged makes it more suitable for high-voltage applications. Thus, the center-tapped transformer rectifier in addition to including electrical isolation has only one diode voltage drop between the source and load making it desirable for low-voltage and high current applications.

2.2.2 Controlled Single Phase Rectifier

The previous rectifiers are classified as uncontrolled rectifiers but once the source and the load parameters are established, the DC level of the output and the power transferred to the load are fixed quantities. As mentioned before that the output voltage of the AC-DC converters using diodes is not controllable because the diodes are not self-controlled switch [8]. Thus, there is a way to control the output by using thyristor instead of a diode. A thyristor is a four-layer (pnpn), three-junction device that conducts current only in one direction similar to a diode.

i) Single Phase Half-Wave controlled Rectifiers

Unlike the diode, the silicon controlled rectifier (SCR) will not to begin to conduct as soon as the source becomes positive. Gate trigger current is the minimum current required to switch silicon controlled rectifiers from the off-state to the on-state at the specified off-state voltage and temperature. Once the SCR is conducting, the gate current can be removed and the SCR remains on until the current goes to zero. Figure 2.6 shows a basic controlled half-wave rectifier.

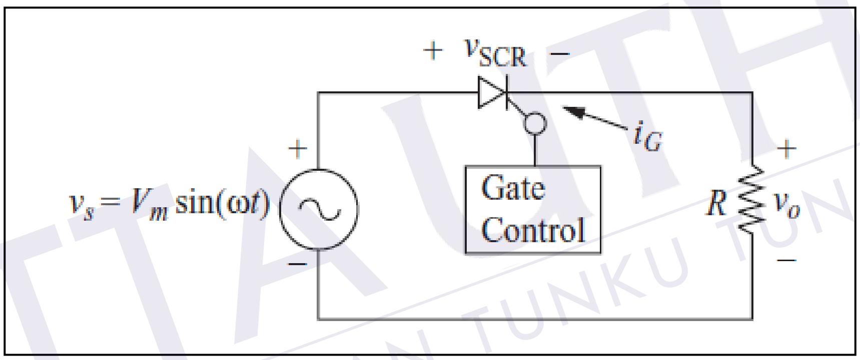


Figure 2.6: Basic half-wave controlled rectifier

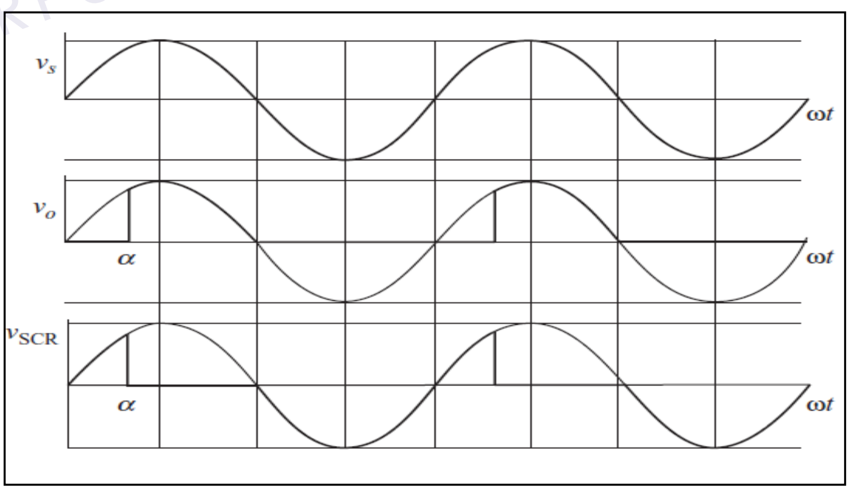


Figure 2.7: Voltage waveform.

ii) Single Phase Full-Wave controlled Rectifiers

Popular AC-DC converters use full-bridge topologies. Full-bridge converters are designed for delivering constant but controllable DC current or DC voltage to the load. Similar to the diode bridge rectifier topology, a versatile method of controlling the output of a full-wave rectifier is to substitute controlled switches such as SCRs for the diode. Because of their unique ability to be controlled, the output voltage and hence the power can be controlled to desire levels. The triggering of the thyristor has to be synchronized with the input sinusoidal voltage in an AC to DC rectifier circuit.

The delay angle α is the angle interval between the forward biasing of the SCR and the gate signal application. Otherwise, if the delay angle is zero, the rectifiers behave exactly like uncontrolled rectifiers with diodes. Figure 2.8 shows a basic controlled full wave rectifier.

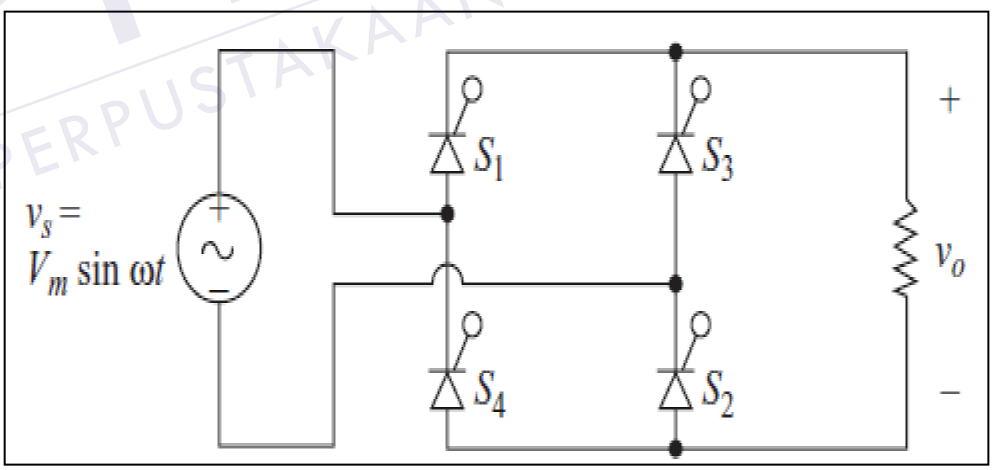


Figure 2.8: Basic full-wave controlled bridge rectifier

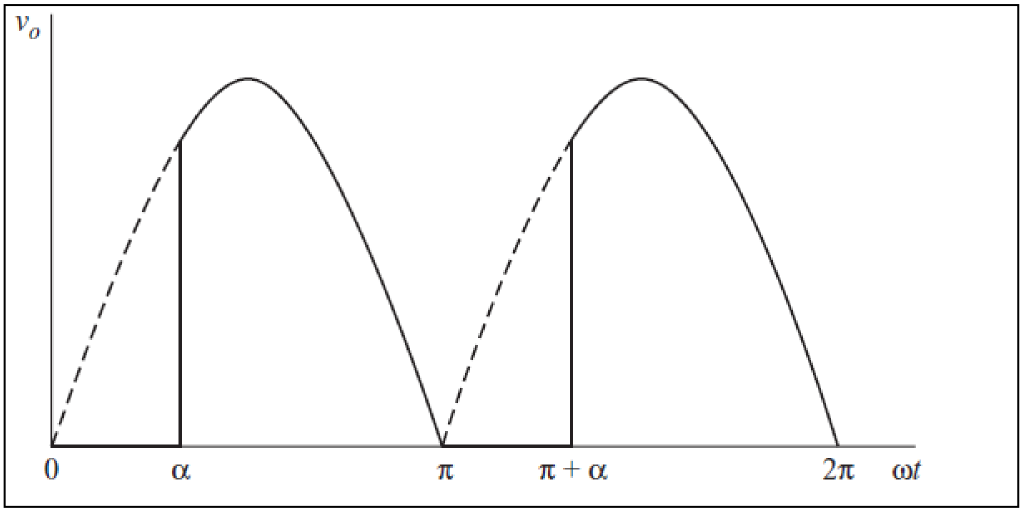


Figure 2.9: Voltage wave forms.

2.2.3 Phase Angle Delay Control

Converter operation in steady-state is best described over a period that begins from the phase α to 2π+ α. This operation involves two circuit modes during a single period of the source waveform depending upon the state of the switches as shown in Figure 2.8. Mode 1 starts when the SCRs T1 and T3 are turned on at an angle α by control pulses applied at their gate terminals. During mode 1, SCRs T1 and T3 are in forward-biased mode and SCRs T2 and T4 are in reverse blocking mode. The current Io flows through the path shown in Figure 2.11. After angle π, the input source voltage become negative but the SCRs T1 and T3 still conducting. Note that the current sink is the model of a high value inductor, voltage across it can change instantaneously but current cannot. Hence, the output voltage, Vo become negative and follows the input voltage, Vs waveform. The input source is supplying power to the load during α to π which is referred also as the rectifier operation.

Mode 2 begins when the SCRs T2 and T4 are turned on at an angle α + π by the control pulses applied at their terminals. The current is steered away from the SCRs T1 and T3 to T2 and T4 effecting a natural commutation. Now thyristors T1 and T3 are in reverse blocking mode. This converter operation in this mode is identical to that mode 1 during the angle from π+α to 2π+α.

There several possible output voltages are shown in Figure 2.11 given duty ratio of 50%. The phase delay angle allows control over the DC output just as duty ratio control permits adjustment of the output in DC-DC converter [8]. Since DC output is of interest and because the output current comes along with a DC source, the average voltage Vo needs to be determined. Its value will be:

$$V_O = \frac{1}{\pi} \int_{\alpha}^{\alpha+\pi} V_M SIN(\omega t)\, d\,\omega t = \frac{2V_M}{\pi} \cos\alpha \qquad (2.1)$$

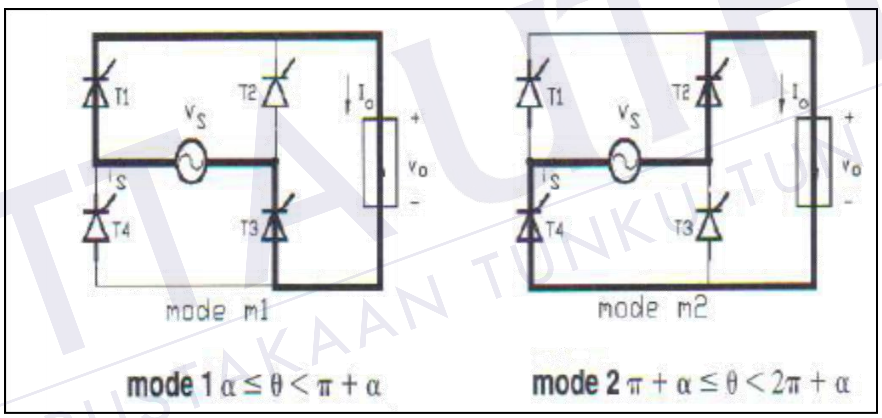


Figure 2.10: Circuit modes.

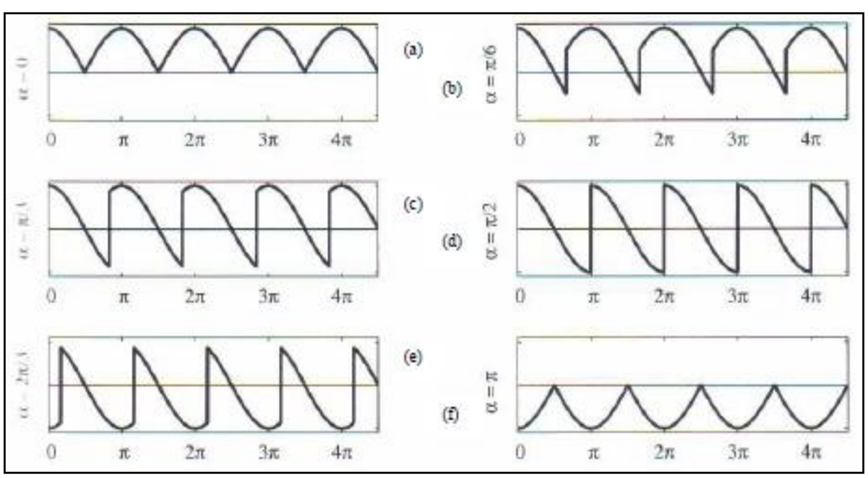


Figure 2.11: Possible output voltage waveform for scr bridge.

2.3 Turning on the ACR methods

Normally can be turn on The SCR by apply pulse to its gate. It can also be turned on by another three alternative methods that include exceeding the forward break over voltage , by excessive heat that allows leakage current , or by exceeding the dv/dt level (allowable voltage change per time change) across the junction. The three alternative methods of turning on an SCR generally cause conditions which should be controlled to prevent the SCR from being turned on when this is not wanted.

2.4 Turning on the SCR by gate triggering

When a positive pulse is applied to the gate of the SCR, it must be large enough to provide sufficient current to the first junction. If the current level of the pulse is sufficient, the first junction will go into conduction and the current flow through it will cause the second junction of the transistor to go into conduction. the current through the second junction will be sufficient to latch up the SCR by supplying an alternative source for the gate current. This means that the current to the gate can be removed and the SCR will remain in conduction. The SCR will commutate when the power supply it is connected to returns to the zero voltage level at 180º or when AC voltage is in reverse polarity (180º to 360º). If the pulse too small that applied to the gate or not enough in duration, the SCR will not turn on [12].

2.5 Dc Motor

DC Machines can be classified according to the electrical connections of the armature winding and the field windings. The different ways in which these windings are connected lead to machines operating with different characteristics. The field winding

can be either self-excited or separately excited, that is, the terminals of the winding can be connected across the input voltage terminals or fed from a separate voltage source (as in the previous section). Further, in self-excited motors, the field winding can be connected either in series or in parallel with the armature winding. These different types of connections give rise to very different types of machines, as we will study in this section.

2.5.1 Separately Excited Machines

- The armature and field winding are electrically separate from each other.
- The field winding is excited by a separate DC source.

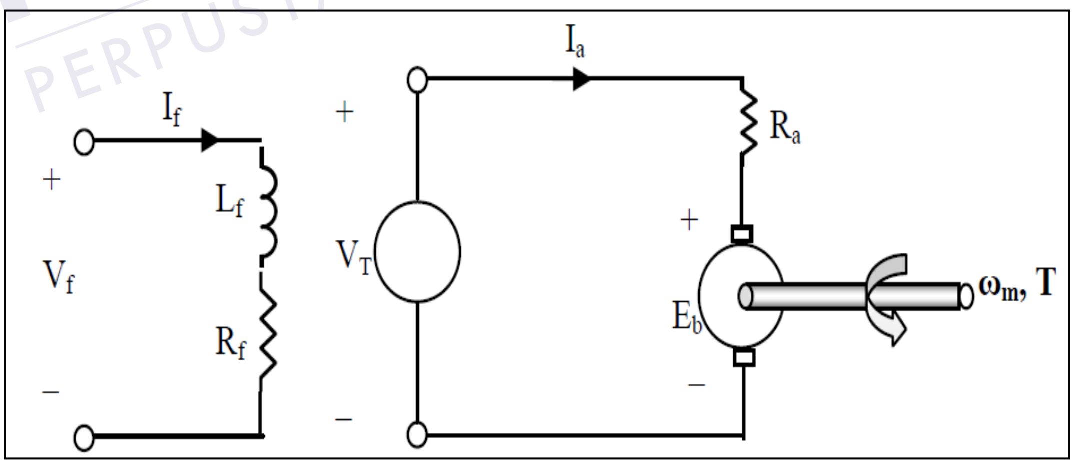


Figure 2.12: Separately excited dc motor

The voltage and power equations for this machine are same as those derived in the previous section. The total input power = $V_f I_f + V_T I_a$

2.5.2 Self Excited Machines

In these machines, instead of a separate voltage source, the field winding is connected across the main voltage terminals.

i) Shunt machine:

- The armature and field winding are connected in parallel.
- The armature voltage and field voltage are the same.

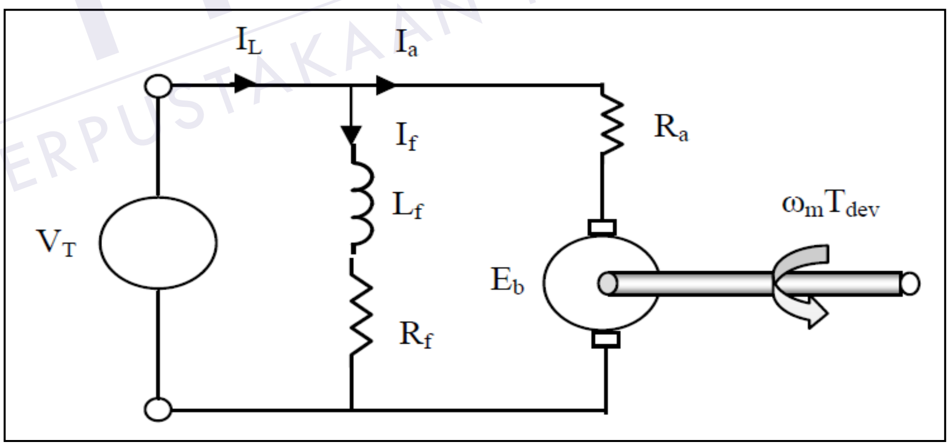


Figure 2.13: Shunt DC motor

In this type of motor, Total current drawn from the supply is:

$$I_L = I_f + I_a \tag{2.2}$$

Total input power = V_T*I_L

ii) Series DC machine

- The field winding and armature winding are connected in series.
- The field winding carries the same current as the armature winding.

A series wound motor is also called a *universal* motor. It is universal in the sense that it will run equally well using either an ac or a dc voltage source. Reversing the polarity of both the stator and the rotor cancel out. Thus the motor will always rotate the same direction irregardless of the voltage polarity.

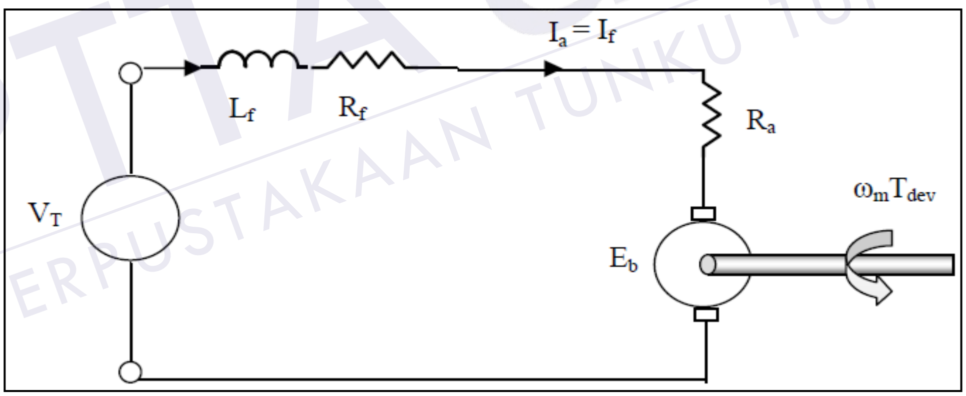


Figure 2.14: Series DC motor.

iii) Compound DC Machine

If both series and shunt field windings are used, the motor is said to be compounded. In a compound machine, the series field winding is connected in series with the armature, and the shunt field winding is connected in parallel. Two types of arrangements are possible in compound motors:

Cumulative compounding - If the magnetic fluxes produced by both series and shunt field windings are in the same direction (i.e., additive), the machine is called cumulative compound.

Differential compounding - If the two fluxes are in opposition, the machine is differential compound. In both these types, the connection can be either short shunt or long shunt [15].

2.6 Control technique

As part of the feedback control system in electrical drives, it is desirable that the relation between the control signal and the average output voltage is linear especially when a linear controller (such as a PI controller) is employed. As an example Figure 2.15 shows a closed loop current control system for a DC motor drive employing a single phase controlled rectifier. In DC drives (or in other type of electrical drives), it is normally necessary to control the motor current since it is, in most of the cases, proportional to the developed motor torque. This is especially true for a DC motor. The reference current (or reference torque) is compared with actual current and the error is fed to the current controller (e.g. PI controller) to generate the control signal V_c.

The firing circuit is responsible in generating the pulses used to trigger the SCRs so that the desired average voltage is produced at the output of the converter. As we have seen before, the relation between a and the average voltage V_a is non-linear due to the cosine term present in the expression. If the relationship between V_c and a is linear, obviously the relationship between V_c and V_a will be non-linear. While it is true that we can linearized (1) for the purpose of designing the controller, this however only valid for a small perturbation around an operating point of the delay angle. On the other hand, if we can establish an inverse cosine relation between vc and a, then the relation between V_c and V_a will become linear.

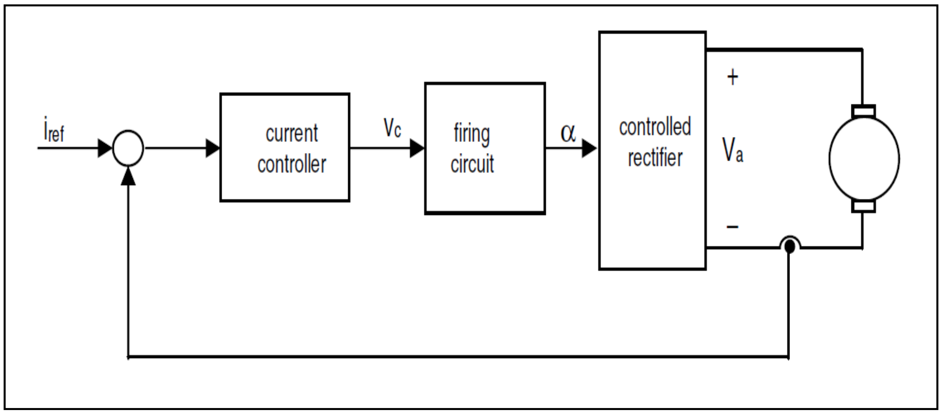


Figure 2.15: Current control loop employing controlled rectifier

2.6.1 PID Controller

PID stands for proportional, integral, derivative are one of the most popular feedback controller widely use in processing industry. It is easy to understand the algorithm to produce excellent control performance.

The PID consists of three basic modes that are proportional modes, integral modes and derivative modes as shown in Figure 2.16. Generally three basis algorithm uses are P, PI and PID. This controller has a transfer function for each modes, proportional modes adjust the output signal in direct proportional to the controller output A proportional controller (K_P) reduced the error but not eliminated it. An integral controller (K_I) will have the effect of eliminating the steady-state error but it may worsen the transient respond. The derivative controller (k_d) will have the effect of increasing the stability of the system, reducing the overshoot and improving the transient respond.

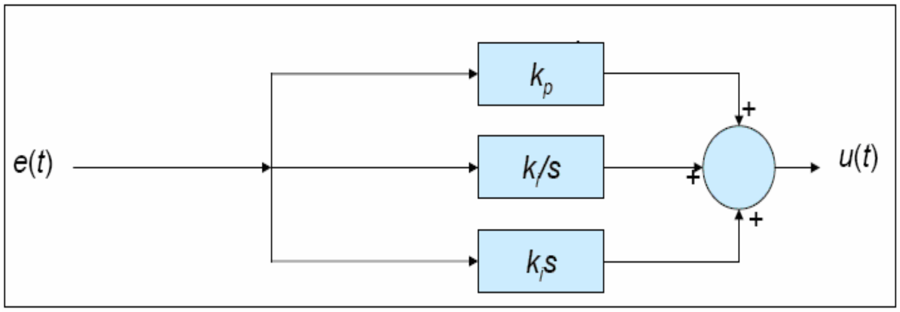


Figure 2.16: Proportional-Integral-Derivative (PID) controllers

In designing PID controller there are several steps to be applied in order to obtain desired output response. It is not necessary to implement all three controllers if not needed, if P or PI controller gives a good enough response then there is no need to implement the derivative controller.

Controllers respond to the error between a selected set point and the offset or error signal that is the difference between the measurement value and the set point. Optimum values can be computed based upon the natural frequency of a system. Too 15much feedback (positive feedback cause stability problems) causes increasing oscillation. With proportional (gain) only control the output increases or decreases to a new value that is proportional to the error. Higher gain makes the output change larger corresponding to the error. Integral can be added to the proportional action to ramp the output at a particular rate thus bring the error back toward zero. Derivative can be added as a momentary spike of corrective action that tails off. Derivative can be a bad thing with a noisy signal [6].

Typical steps for designing a PID controller are

i) Determine what characteristics of the system need to be improved.

ii) Use K_P to decrease the rise time.

iii) Use K_D to reduce the overshoot and settling time.

iv) Use K_I to eliminate the steady-state error.

2.6.2 Fuzzy Logic Control

Fuzzy control is an artificial intelligence technique that is widely used in control systems as shown in Figure 2.17. It provides a convenient method for constructing nonlinear controllers from heuristic information.

Fuzzy controller have achieved some polarity due to the convenient way in which desired nonlinearities may be introduced, especially when no model of the controller process in available but operator experience may be used as a guide to formulating rules. Fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain. In a fuzzy logic controller (FLC), the dynamic behaviour of a fuzzy system is characterized by a set of linguistic description rules based on expert knowledge. The expert knowledge is usually of the form.

IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred).

Since the antecedents and the consequents of these IF-THEN rules are associated with fuzzy concepts (linguistic terms), they are often called fuzzy conditional statements.

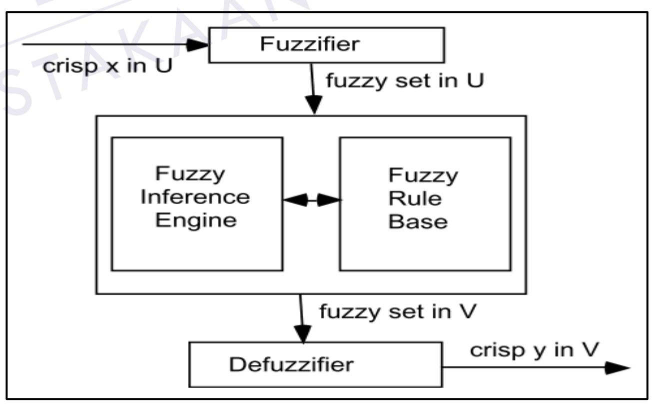
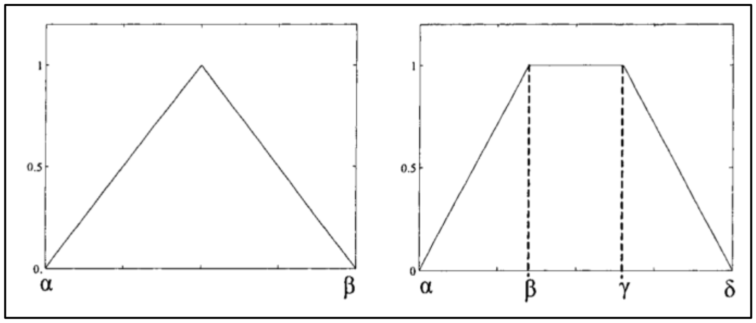


Figure 2.17: Fuzzy logic control diagram

Membership function of FLC is explained as below:

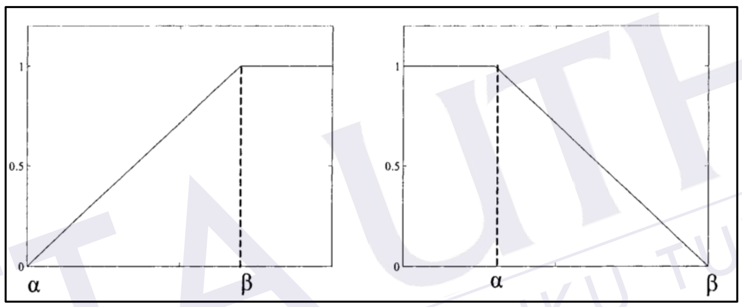
Let X denotes the universe of discourse of a fuzzy set A. A is completely characterized by its membership function μA:

$$\mu A : X \longrightarrow [0, 1]$$



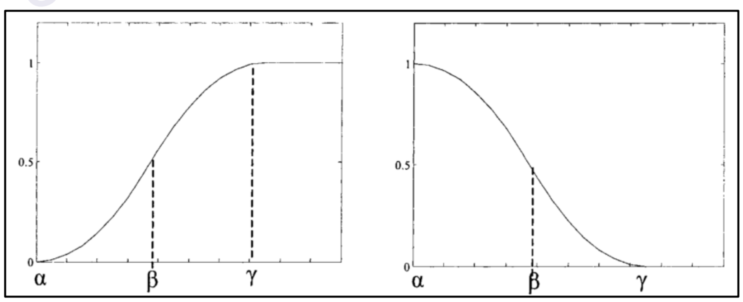
a) b)

Figure 2.18: a) Triangular membership function b) Trapezoid membership function



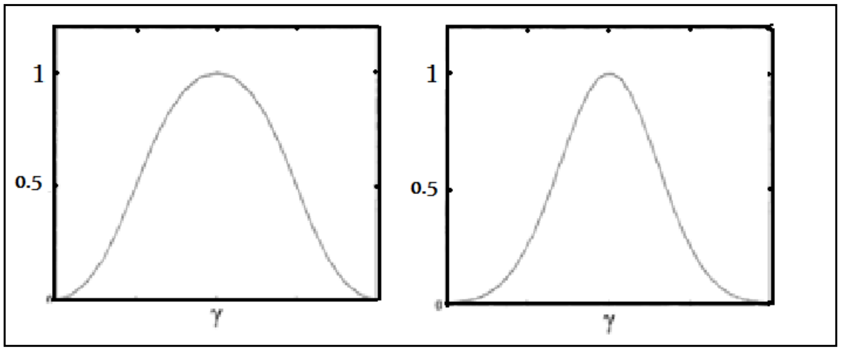
a) b)

Figure 2.19: a) Monotonically increasing linear membership function b) monotonically decreasing linear membership function.



a) b)

Figure 2.20: a) Monotonically increasing sigmoidal membership function b) monotonically decreasing sigmoidal membership function.



a) b)

Figure 2.21: a) π membership function, b) Gaussian membership function

A typical rule in a Sugeno fuzzy model has the form

If Input 1 = x and Input 2 = y, then Output is $z = ax + by + c$

For a zero-order Sugeno model, the output level z is a constant $(a=b=0)$.

The output level z_i of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = x and Input 2 = y, the firing strength is

$$w_i = Andmethod\left(F_1(x), F_2(y)\right) \quad (2.1)$$

Where $F_{1,2}(.)$ are the membership functions for Inputs 1 and 2.

The final output of the system is the weighted average of all rule outputs, computed as:

$$FinalOutput = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \quad (2.2)$$

Where N is the number of rules.

A Sugeno rule operates as shown in the following diagram.

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