نموذج رقم (1)

إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Design of Fuzzy Controller for LCL Resonant Converters

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وإن هذه الرسالة ككل أو أي جزء منها لم يقدم من قبل لنيل درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية أخرى.

DECLARATION

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification

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Date: 28/10/2014م التاريخ:

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Design of Fuzzy Controller for LCL Resonant Converters

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This thesis is submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering

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بسم الله الرحمن الرحيم

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **رفعت يوسف حسين دهمان** لنيل درجة الماجستير في كلية *الهندسة* / قسم **الهندسة الكهربائية – أنظمة التحكم** وموضوعها:

تصميم المتحكم الضبابي للتحكم بالمحول الرنين المتسلسل ثابت الجهد-ثابت الجهد
Design of Fuzzy Controller for LCL Resonant Converters

وبعد المناقشة التي تمت اليوم الأربعاء 28 ذو الحجة 1435هـ، الموافق 2014/10/22م الساعة العاشرة صباحاً، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق،،،

مساعد نائب الرئيس للبحث العلمي والدراسات العليا

أ.د. فؤاد علي العاجز

DEDICATION

I dedicate this thesis to my Parents in recognition of their endless help and support. I also dedicate this work to my wife and to my children, Yusuf and Mohammed who are my most precious thing in this life.

ACKNOWLEDGMENTS

First and foremost, I thank ALLAH for giving me the strength and health to let this work see the light.

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ABSTRACT

The LCL Resonant Converter plays a great role in many of the artificial applications like the sources of the radar power, the aerospace sources, the solar cells and recently it was used in the networks and communication system. It is used to convert the DC voltage to the needed value with no ripple or errors or losses and with high efficiency and in quick time. It needs intelligent controller such as the fuzzy logic controller because it is easy to use and doesn’t strictly need any mathematical model of the plant. It is based on operator experience, and it is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant. In addition, fuzzy logic simplifies dealing with nonlinearities in systems. The advantage of fuzzy logic control is that the linguistic system definition becomes the control algorithm.. In this thesis two methods of the fuzzy logic controller were used: the Mamdani and the Sugeno that control the gate of the MOSFET to rise the efficiency and to get a better result. After that we made a comparison between these two types of fuzzy controllers to find the better result. Also we made another comparison between this result and previous results for the same LCL Resonant Converter. The controller was tested (Mamdani and Sugeno) with the LCL RC by using the matlab/simulink after designing a model to stimulate the features of the converter to get the best result as much as possible.

الملخص

يلعب محول الرنين المتسلسل ثابت الجهد ثابت الجهد دورا مهما في العديد من التطبيقات الصناعية مثل :مصادر طاقة الرادار، ومصادر القمر الصناعي، ويكثر استخدامه في الخلايا الشمسية، وحديثا دخل استخدامه في مجال الاتصالات والشبكات وفي الفضاء أيضا .وهو يقوم بتحويل الجهد الثابت من مستوى معين من الفولت الى المستوى المطلوب استخدامه ولكي يتم الحصول على خرج فولت مناسب بدون تموجات وأخطاء وبسرعة عالية وبدون فقد وبكفاءة عالية .لذلك يحتاج الى متحكم من نوع ذكي مثل المتحكمات الضبابية حيث أن للمتحكمات الضبابية مميزات كثيرة مثل سهولة نسبية في التصميم فهو لا يحتاج معرفة دقيقة عن المعادلات الرياضية التي تصف النظام المراد التحكم به , وهو يعتمد على خبرة المصمم كما يعمل بشكل ممتاز مع الأنظمة الاخطية.

في هذه الرسالة تم استخدام نوعين من المتحكم الضبابي الأول من نوع Mamdani والاخر من نوع Sugeno للتحكم بخرج الفولت من المحول الرنين المتسلسل ثابت الجهد ،وهما يتحكمان بفتح وغلق مفتاح الموسفت الموجود داخل المحول ،لتحسين أداء دائرة المحول والحصول على نتيجة خرج فولت مناسب بدون تموجات واخطاء وبعد ذلك نقوم بعمل مقارنة بين هذين النوعين من المتحكم الضبابي لمعرفة أفضل نتيجة لخرج الفولت، وأيضا عمل مقارنة مع أعمال سابقة لنفس المحول الرنين المتسلسل ثابت الجهد ثابت الجهد ،وسيتم اختبار المتحكم الضبابي للنوعين على المحول الرنين المتسلسل ثابت الجهد ثابت الجهد باستخدام برنامج الماتلاب/ سمولينك عن طريق تصميم مودل ليحاكي المواصفات الموجود بالمحول لمعرفة أفضل نتيجة نحصل عليها.

Computer Software Used:

- Microsoft ®Windows 8 Operating Systems
- Microsoft ®Word 2010
- MATLAB ®Version R2013a
- Simulink Version
- Acrobat Reader X

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Nomenclature

Digital Converter	**DC**
Resonant Converter	**RC**
Center of Gravity	**COG**
Fuzzy Log	**FL**
Fuzzy Logic Controller	**FLC**
Fuzzy Logic System	**FLS**
Membership Function	**MF**
Pulse Width Modulation	**PWM**
Takagi- Sugeno-Kang	**TSK**
Weighted Average Method	**WAM**
Direct Current	**DC**
Error	**e**
Previous Error	**Pe**
Change of Error	**Ce**
Quality Factor	**Q**
Reference Voltage	V_r
Load Voltage	V_l
Series Resonant Converter	**SRC**
Parallel Resonant Converter	**PRC**
Series Parallel Resonant Converter	**SPRC**

CHAPTER1 INTRODUCTION

First let us define a resonant converter as a power conditioning system which utilizes a resonant LCL circuit as a part of the power conversion process. All resonant converters operate in essentially the same way: a square pulse of voltage or current is generated by the power switches and this is applied to a resonant circuit. Energy circulates in the resonant circuit and some or all of it is then tapped off to supply the output. While basically simple, this principle can be applied in a wide variety of ways, creating a bewildering array of possible circuits and operating modes.

The Resonant Converter (RC) is found in wide applications in many space and radar power supplies. Among various RCs LCL, LCC, and LCL-T topologies are broadly used. In recent years, the design and development of various DC–DC resonant converters (RCs) have been focused for telecommunication and aerospace applications. It has been found that these converters experience high switching losses, reduced reliability, electromagnetic interference (EMI), and acoustic noise at high frequencies. [1].

The LCL tank circuit-based DC–DC RC which is a good choice for dc power supplies for industrial, since the resonant converter is directly converted into dc voltage by switching frequency variations. Above applications require high frequency, high efficiency conversion systems thus making resonant inverters more ideal. Resonant inverters have been recognized as the next generation power conversion circuits that can best suit for the above requirements because of their low component costs, small component sizes and high efficiency. Also the LCL and LCC Resonant Full Bridge Converters (RFB) are new, high performance DC-DC converters which cater above requirements. Also owing to their small size and lightweight, they could find their place in the above applications. The common limitation of two element resonant topologies can be overcome by adding a third reactive element termed as modified series resonant converter (SRC).

This research proposes a system that use fuzzy controller for a modified LCL RC[2].

1.1 Switch-Mode DC-DC Converters

Switch-mode DC-DC converters are used to convert the direct DC input to a controlled DC output at a desired voltage level. Switch-mode DC-DC converters include buck converters, boost converters, buck-boost converters, Cuk converters and full-bridge converters, etc. Among these converters, the buck converter and the boost converter are the basic topologies. Both the buck-boost and Cuk converters are combinations of the two basic topologies. The full-bridge converter is derived from the buck converter [3].

There are usually two modes of operation for DC-DC converters: continuous and discontinuous. The current flowing through the inductor never falls to zero in the continuous mode. In the discontinuous mode, the inductor current falls to zero during the time the switch is turned off. Only operation in the continuous mode is considered in this dissertation [3].

1.2 LITERATURE REVIEW.

The developments related to the study, research and applications of resonant converters are increasing nowadays because of their outstanding performance. The researches in this field have been shown more interest by many researchers focused for telecommunication and aerospace applications The developments of load independent converters for various applications have been focused by the research publications. It has also been suggested to design resonant converter with three reactive components for better regulation and performance. The LCL tank circuit based DC-DC resonant converter has been experimentally demonstrated and reported by many authors.

1.2.1 Forward DC-DC Converter Topologies

Leu et al (1991), Min Chen et al (2002), Jianping Xu et al (1999) have demonstrated forward DC-DC converter topologies. The major disadvantages of two-switch forward converters are hard switching and the large filter inductor. Hard switching leads to high switching loss for high frequency operation. In addition, the voltage-second on the output inductor is much higher in two-switch- forward converters than in half-bridge and full bridge converters. Because of these penalties, two-switch forward converters are not very desirable for meeting higher efficiency[4].

1.2.2 Soft-Switching Techniques for PWM Full Bridge Converters

Lee et al (1990), Lotfi et al (1992), Dalal and Tsai (1993), Choet al (1994), Hua and Lee (1994), Chen et al (1995), Hua and Lee (1995), Korotkov et al (1997), Xinbo Ruan and Yangguang Yan (2000), Wong et al(2000) has demonstrated soft-switching techniques for PWM full bridge converters. The major problems of this converter are the high circulating current during normal operation and a large amount of conduction loss. Yang et al (2001) a range winding approach is proposed to deal with the settling time operation problem. The concept of a range winding solution is to change the transformer turns ratio according to different input voltages, so that the transformer can be optimized for high input voltage[5].

1.2.3 DC-DC Buck and Boost Type Converter

In Jang et al (2006), a holdup time extension circuit is proposed to deal with the holdup time operation problem. The concept of the holdup time extension circuit is to employ an additional DC-DC boost type converter for the higher voltage gain required for holdup time.

To solve the holdup time issue in buck-type PWM converters boost-type PWM converters are proposed in Lu et al (2006). The dual active boost converter (DAB) can achieve ZVS and be designed optimally at nominal conditions. During holdup time, due to the boost gain function, DAB can achieve enough gain. Thus, the isolated boost converter can achieve higher efficiency than conventional buck-type PWM converters. However, the drawbacks of the isolated boost converter are the ZVS is lost at light load, the primary side switch turn-off current is relatively high, and hence leads to relatively high turn-off switching loss[6].

1.2.4 LCL Resonant Converter

The LCL tank circuit based DC-DC resonant converter has been experimentally demonstrated with open loop by Oruganti and Lee (1985), Liu (1985), Raju and Seshagirirao Doradla (1995), Calderira et al (1998), Tschirhart and Jain (2008). A three element LCL resonant converter capable of driving voltage type load with load independent operation is analyzed using state space approach. The operation of the converter with variable frequency control was reported. Wang et al (2004) has experimentally demonstrated an LCL load resonant inverter for inductive power transfer applications is investigated[7].

1.2.5 LCL-T Resonant Converter

Vijayakumar Belaguli and Bhat (2000) have experimentally demonstrated the open loop series parallel resonant converter with independent load operated at resonant frequency. The converter was operated in Discontinuous Current Mode of (DCM) operation and the performance characteristics are presented. The converter was analyzed using the state space approach and optimized for peak component stresses. The characteristics curves were obtained using the PROMATLAB and SPICE simulation. The performance of the designed converter for variations in supply voltage as well as load were studied and presented. Mangat et al (2004) has experimentally demonstrated modified asymmetrical pulse width modulated resonant DC–DC converter topology. Borage et al (2005) have demonstrated the open loop LCL-T resonant converter with constant current output fed with resistive load. The A.C. analysis is used to drive the voltage and current rating of the components, converter gain and component stresses. It was found that the converter exhibits load-independent voltage and current gain at resonant frequency. Various methods for the control of output current over wide load range and against variation in input dc voltage are presented. Borage et al (2006), Borage et al (2007) has developed the LCL-T half bridge resonant converter operated in constant current power supply. The LCL-T half bridge resonant converter with clamp diodes was described and simulated results demonstrating inherent constant current-constant voltage characteristics of the converter were presented. The output current / voltage are sensed for every change in load due to the output voltage or current which increase linearly. In this case, the feedback control circuit has not been considered.

Mangesh Borage et al (2009) has demonstrated design of LCL-T resonant converter including the effect of transformer winding capacitance and Borage et al (2009) has demonstrated the characteristics of asymmetrical duty cycle controlled LCL-T resonant converter using state space model. Four distinct operating modes were identified and operated in different conditions. The zero voltage switching operation has been used to operate the switches in the asymmetrical duty cycle control and clamped mode control. These controllers are derived and compared with the performance[8][9].

1.2.6 LCC Resonant Converter

The series parallel resonant converter operated in both the continuous capacitor voltage mode and the discontinuous capacitor voltage mode has been demonstrated and presented using state space approach by Bhat and Shashi Dewan (1989), Bhat et al (1992), Ashoka Bhat (1993), Agarwal et al (1993), Sabate et al (1995). The closed-form expressions are derived for steady-state operation, converter gain, peak component stresses and their ratings. An optimization procedure with a design example has been presented. It was observed that the optimum point lies in the discontinuous capacitor voltage mode. Sivakumaran and Natarajan (2006) have demonstrated a CLC series parallel resonant converter using FLC which regulates the output voltage of Series parallel resonant converter (SPRC) for the load regulation and line regulation. The performance of controller has been evaluated and found that the load independent operation may not be possible. Chew China and Eng Sng (2009) and have demonstrated LCC series parallel resonant converter using robust control method. This method was used to vary the converter gain. The closed loop operation was presented using PI controller with load independent operation. The series parallel resonant converter with two significantly different sets of resonant tank parameters validates the technique. The robust control methods were compared with the conventional frequency control and presented. Juan Diaz et al (2010) demonstrated the PRC with medium output voltage and power, having a voltage gain greater than unity, as well as low stress in the components. Short-circuit operation mode was tested with a fixed-frequency variable-duty-control strategy. Moreover, this converter has also been tested with a mixed control strategy, and it has demonstrated that it is possible to reduce the output voltage down to nearly zero. For this operation mode, snubbers must be used; otherwise, the efficiency drops dramatically[10].

1.2.7 Fuzzy Controller Based DC-DC Converter

Balestrino et al (2002), Maftavelli (1997), Vidal et al (2004) have developed a scheme with fuzzy logic. In this scheme, the load independent operation was not considered and power handling capacity of the converter was found to be poor. Using human linguistic terms and common sense, several fuzzy logic controllers have been developed and implemented for DC–DC converters. These controllers have shown promise in dealing with nonlinear systems and achieving voltage regulation in buck converters. Correa and Farret (2003) have demonstrated a

DC/AC series resonant converter with a fuzzy logic controller. They have used two control approaches one was at the input stage (DC/AC) and another one was at the output stage (AC/AC). The performances of these controllers were compared and FLC was found to exhibit better performance. Qiu et al (2004) has demonstrated different approaches which include the fuzzy logic control (FLC). This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. The FLC approach with same control rules can be applied to several DC–DC converters. However, some scaling factors had to be tuned according to converter topology and parameters. The authors utilized the proposed control technique for Buck-Boost converter and demonstrated. The evaluation of DSP-Based PID and fuzzy controllers for DC-DC converters has been demonstrated by Liping Guo et al (2009) and found that under load changes, the fuzzy controller resulted in less oscillation, but the peak variation was higher in a few cases (decreasing load).

Bor-Ren Lin et al (2011) has demonstrated a novel dual resonant converter with two transformers. An active-clamp circuit is employed in the converter to limit the voltage stresses of power switches. In this case, the efficiency of the converter was 89.8% at full Resistive load[11].

1.3 THESIS CONTRIBUTION.

In this thesis, we implemented a system that controls the output voltage of an LCL resonant converter so that it can get to improve the settling time and the ripple of the output voltage of the system. The fuzzy controller will be implemented using by two methods, Mamdani method and Sugeno method and making comparison with it, output gain and inputs gain of the fuzzy controllers by using Matlab/Simulink.

1.4 OUTLINES OF THE THESIS.

This thesis consists of four chapters. Chapter 2 presents the DC-DC Converter model. Chapter 3 presents a review and introduction to fuzzy logic and its application, fuzzy sets operations, the main concepts in fuzzy sets such as membership functions, and linguistic variable. Chapter 4 presents analysis and simulation results of the fuzzy controller, while the last chapter concludes this thesis.

CHAPTER 2 DC-DC CONVERTERS

2.1 CONVERTER

In electrical engineering, power engineering and the electric power industry, power conversion is converting electric energy from one form to another. On the application side, the end user uses the power generated to run his appliances. These appliances in turn use different types of voltage (direct or alternating) with different levels of magnitude. Hence, there is a need to convert these voltages as per requirement. That is why converters come into picture? One may ask a question, why don’t we reduce the magnitude levels using a potential divider? If at all the voltage or power level is the only concern for the appliances. But, there lies an urge to reduce the loss component in the circuit (to improve efficiency), make it compact, incorporate changes in parameters if required (like frequency adjustments), as well as the most important reason to make it economical[12].

Considering all the above factors, the necessity of a converter is well defined. Converters are classified into 4 types depending on the type and magnitude level of voltages is concerned:

1. AC-AC converters
2. AC-DC converters
3. DC-DC converters
4. DC-AC converters

We deal with the DC-DC converters, so let us have a quick introduction about the DC-DC converters.

2.2 DC-DC CONVERTER

A DC-DC converter is an electronic circuit power class converter which converts a source of direct current (DC) from one voltage level to another .If the voltage magnitude level at the output is greater than the input, then the converter is called a boost converter, while if the voltage magnitude level at the output is less than the input, then the converter is called a buck converter[13].

One may think, why do not we use a linear regulator for reducing the voltage? The answer is that the linear regulators prove to be efficient over the switching regulators (such as the above converters) when the output is lightly loaded or when the desired output voltage is very close to the source voltage. Also linear regulators are void of magnetic circuit involving transformers or inductors thus resulting in a relatively smaller circuit. Other than these conditions if a linear regulator is used, the BJT which is usually used for regulation acts as a resistor, with the power loss across it. In order to make loss due to resistive drop almost negligible, we use switching regulators.

2.3 RESONANT DC-DC CONVERTER

In resonant converter the imperfect switching is a major contributor to power loss in converters and it’s include resonant switch converters, load resonant converters, and resonant dc link converters. Above applications require high frequency, high efficiency conversion systems thus making resonant inverters more ideal. Resonant inverters have been recognized as the next generation power conversion circuits that can best suit for the above requirements because of their low component costs, small component sizes and high efficiency[14].

There are many types of RC which have equivalent circuit like LCL, LCC, and LCL Topology.

The state space analysis of these circuits is:

1) The switches, diodes, inductors, and capacitors used are ideal;
2) The effects of snubber capacitors are neglected;
3) Losses in the tank circuit are neglected;
4) DC supply used is assumed to be smooth;
5) Only fundamental components of the waveforms are used in the analysis;
6) Ideal high-frequency transformer with turns ratio n = 1; (that to provide voltage transformation and ohmic isolation between the dc source and the load).
7) The state equation describes the state during the period $tp-1 < t < tp$ where $tp-1$ is the starting instant of continuous conduction mode and tp is the instant when the continuous conduction mode ends.

2.4 MODIFIED SERIES RESONANT CONVERTER.

A Series Resonant Full Bridge Converter (SRC) modified by adding an inductor in parallel with the transformer primary is presented. This configuration is referred to as an “LCL Resonance Full Bridge Converter .”A three element (LCL) Resonance

Full Bridge Converter capable of driving voltage type load with load independent operation is analyzed. In such converters have load independent characteristics, there is no analysis or design procedure available. It is shown in this project that these types of converter requires a very narrow range of frequencies control from full load to very light loads and can operate with load short circuit while processing the desirable features of the SRC. The resonance converter operating in the above resonance (lagging power factor) mode has a number of advantages (e.g. No need for lossy snubbers and di/dt limiting inductors). Therefore, the proposed converter configuration in the above resonance mode, State-space approach is used for the converter analysis. A modified SRFB Converter with capacity output filter has been presented[15].

2.4.1 Design of an RC

The Following Figure illustrates:

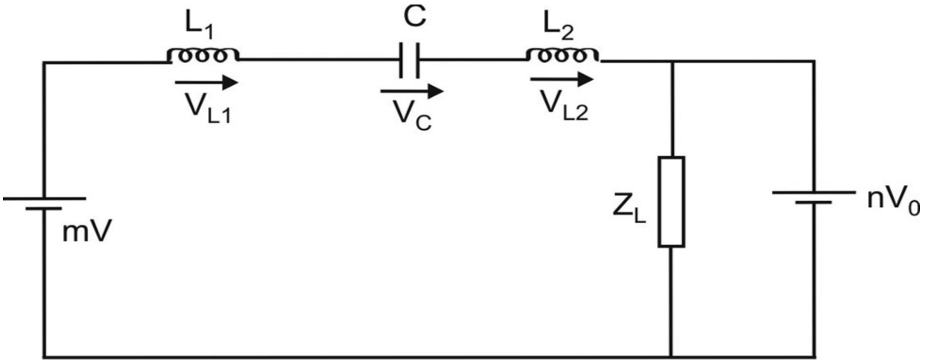


Figure 2.1: Equivalent circuit model of the LCL RC[14]

In order to pursue the analysis, a converter with the following specification is designed: power output = 133W, minimum input voltage = 125 V, minimum output voltage = 100 V, maximum load current = 1.33 A, maximum overload current = 4 A. The high-frequency transformer turns ratio is assumed to be unity[14].

The input RMS voltage to the diode bridge is

$$(D_1 - D_2)(V_{L2}) = \frac{2\sqrt{2}\,V_o}{\pi} \qquad (2.1)$$

The input RMS current at the input of the diode bridge is

$$I_d = \frac{\pi\, I_o}{2\sqrt{2}} \qquad (2.2)$$

The load impedance

$$Z_L = \frac{100}{1.33} = 75.18\,\Omega \qquad (2.3)$$

The reflected ac resistance on the input side of the diode bridge is

$$V_{ac} = \frac{V_{L2}}{I_d} \qquad (2.4)$$

$$\frac{V_{L2}}{I_d} = \frac{2\sqrt{2}\, V_o/\pi}{\pi\, I_o/2\sqrt{2}} = \frac{8\, V_o}{I_o \pi^2} \qquad (2.5)$$

$$\frac{\sqrt{L_2}}{\sqrt{C}} = \frac{8\, Z_L}{\pi^2} = \frac{8 \times 75}{\pi^2} = 60.8\,\Omega \qquad (2.6)$$

Since the switching frequency is 50 kHz

$$\frac{1}{2\pi\sqrt{L_1} \times \sqrt{C}} = 50 \times 10^3 \quad L_{L1} = 60.8\sqrt{C} \quad (2.7)$$

$$\sqrt{C} = \frac{\sqrt{L_1}}{60.8} \qquad (2.8)$$

$$\frac{1}{2\pi\sqrt{L_1} \times \sqrt{L_1}/60.8} = 50 \times 10^3 \qquad (2.9)$$

$$\frac{60.8}{2\pi L_{L1}} = 50 \times 10^3 \qquad (2.10)$$

The quality factor Q and resonant frequency fo of the LCL

RC are given as:

The following definition is also mathematically accurate to the quality factor Q,

$$Q = \frac{W_o}{W_2 - W_1} \qquad (2.11)$$

$$f_o = \frac{1}{2\pi\sqrt{(L_1 + L_2) \times C}} \quad and \; Q = \frac{\sqrt{(L_r/C}}{Z_L} \tag{2.12}$$

$$L_r = L_1 + L_2 \;\; and \; C_r = C \tag{2.13}$$

From the aforementioned equation, we get the values of L1 as 185µH and L2 as 10 µH and C as 0.052µF.

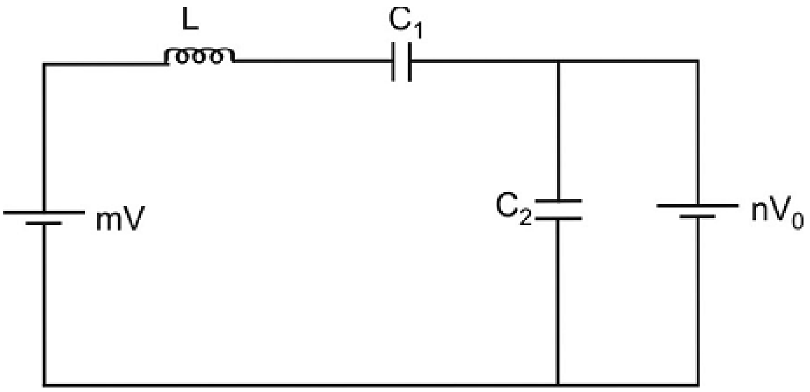


Figure 2.2: Equivalent circuit model of the LCC[14]

The equivalent circuit of the LCC RC is shown in Figure 2.2. The quality factor and resonant frequency of the LCC RC are given

$$Q = \frac{Z_L}{\sqrt{\frac{L}{\frac{C_1 \times C_2}{C_1 + C_2}}}} \quad and \;\; f_o = \frac{Z_L}{2\pi\sqrt{L\frac{C_1 \times C_2}{C_1 + C_2}}} \tag{2.14}$$

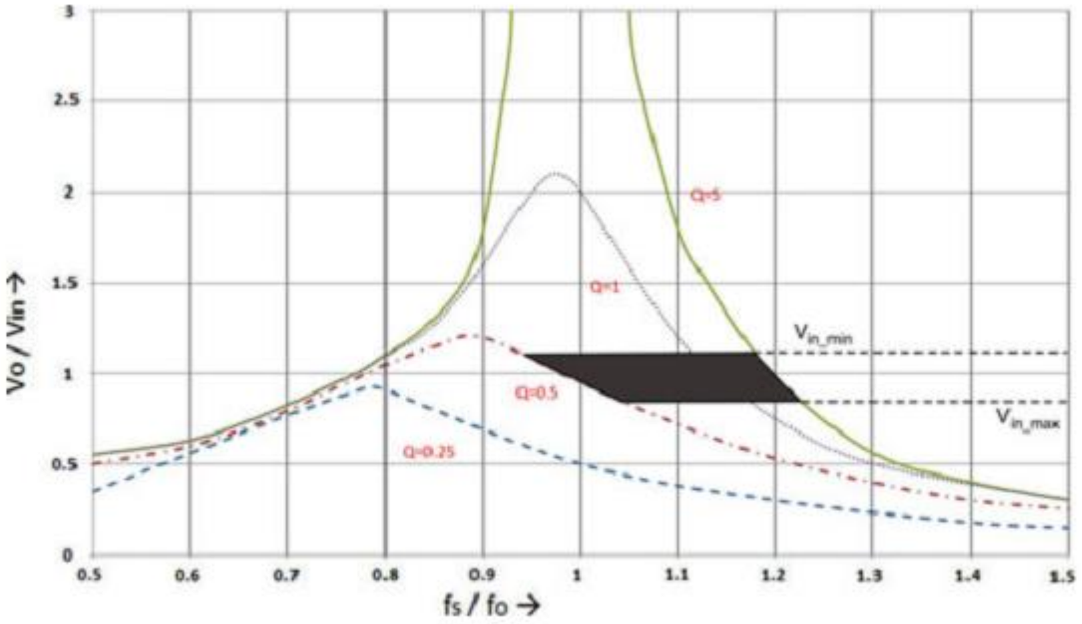


Figure 2.3 DC gain characteristics and operating region of the LCC RC[15].

Figure 2.3 shows the dc characteristic of the LCC RC. The major problems of the SRC are light-load regulation, high circulating energy, and high turn-off current at nominal input voltage. The major problems of the PRC are high circulating energy and high turn-off current under the high input-voltage condition. When compared with the SRC, the operating region is much smaller. At light load, the frequency does not need to change too much to keep output voltage regulated. So a light-load regulation problem does not exist in the PRC. The LCC resonant tank can be considered as the combination of SRC and PRC thereby combining the advantages of both. Figure 2.3 shows that the maximum gain, which is determined by Q, affects the operating range of the switching frequency regulating the output voltage under line variation. From the graph, it can be observed that LCCRCs can achieve a narrow switching frequency range with load change. Under light-load conditions, the circulating energy is smaller. The LCC has two resonant frequencies: series resonant frequency and parallel resonant frequency. Although operating at the series resonant frequency is desirable for high efficiency, when doing so, ZVS is lost for certain load conditions. Thus, the operating region is designed to be on the right-hand side of the parallel resonant frequency to achieve ZVS under all load conditions. Unfortunately, like the PRC and SRC, for the LCC, the circulating energy and the turn-off current of the device also increase at the nominal input voltage Vin max. In sum, to deal with a wide input-voltage range, all these traditional RCs encounter some problems. To achieve higher efficiency, LCL resonant topologies should be considered. LCL-T and LCCRCs encounter problems while dealing with a wide input voltage range. Meanwhile, under the nominal condition, the LCL RC operates very close to the resonant frequency, which is the best operation point to accomplish high efficiency. In addition, voltage gains of different Q converge at the series resonant point. The LCL resonant tank parameters can be optimized to achieve high efficiency for a wide load range. As a result, holdup time extension capability is accomplished without sacrificing the efficiency under the nominal condition. The LCLRC is considered as one of the most desirable topologies for a wide input-voltage range[16].

CHAPTER 3 FUZZY CONTROL

3.1 FUZZY LOGIC

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth- truth values between "completely true" and "completely false". As its name suggests, it is the logic underlying modes of reasoning which are approximate rather than exact. The importance of fuzzy logic derives from the fact that most modes of human reasoning and especially common sense reasoning are approximate in nature [17].

Fuzzy logic was developed by Lotfi A. Zadeh in the 1960s in order to provide mathematical rules and functions which permitted natural language queries. Fuzzy logic provides a means of calculating intermediate values between absolute true and absolute false with resulting values ranging between 0.0 and 1.0. Fuzzy logic calculates the shades of gray between black/white and true/false.

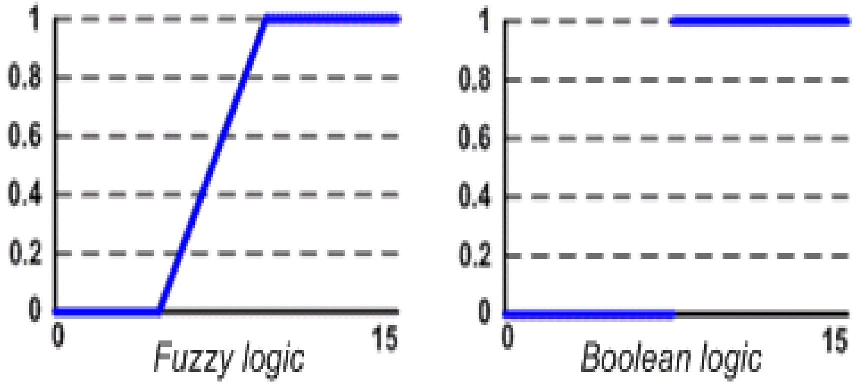


Figure 3.1: Fuzzy Logic vs. Boolean Logic

Fuzzy Logic deals with those imprecise conditions about which a true/false value cannot be determined. Much of this has to do with the vagueness and ambiguity that can be found in everyday life. For example, the question: *Is it HOT outside?* Probably would lead to a variety of responses from those asked. These are often labeled as subjective responses, where no one answers is exact. Subjective responses are relative to an individual's experience and knowledge. Human beings are able to exert this higher level of abstraction during the thought process. For this reason, Fuzzy Logic has been compared to the human decision making process. Conventional Logic (and computing systems for that matter) is by nature related to the Boolean

Conditions (true/false). What Fuzzy Logic attempts to encompass is that area where a partial truth can be established, that is a gradient within the true/false realm [17].

3.2 THE OPERATIONS OF FUZZY SETS

In the classical sets there are basic operations that are found, such as intersection and union between sets, complement of set. If we have two sets (**A** and **B**) and these sets are subsets of universe (**U**).

3.2.1 Union

The membership function of the Union of two fuzzy sets A and B with membership functions μ_A and μ_B respectively is defined as the maximum of the two individual membership functions. This is called the *maximum* criterion.

$$\mu_{A \cup B} = max\ (\mu_A, \mu_B) \qquad (3.1)$$

The Union operation in Fuzzy set theory as shown in figure 3.2 is the equivalent of the **OR** operation in Boolean algebra.

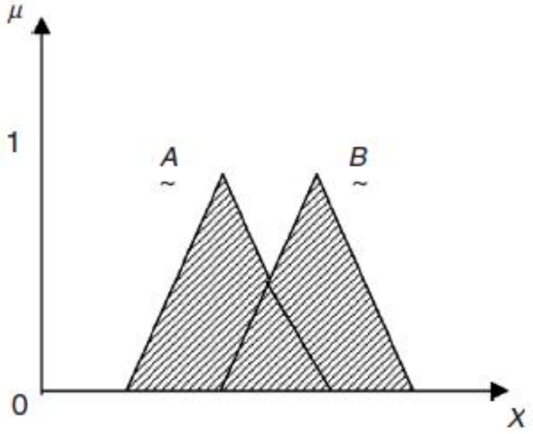


Figure 3.2: A OR B

3.2.2 Intersection

The membership function of the Intersection of two fuzzy sets A and B with membership functions μ_A and μ_B respectively is defined as the minimum of the two individual membership functions. This is called the *minimum* criterion.

$$\mu_{A \cap B} = min\ (\mu_A, \mu_B) \qquad (3.2)$$

The Intersection operation in Fuzzy set theory as shown in figure 3.3 is the equivalent of the **AND** operation in Boolean algebra.

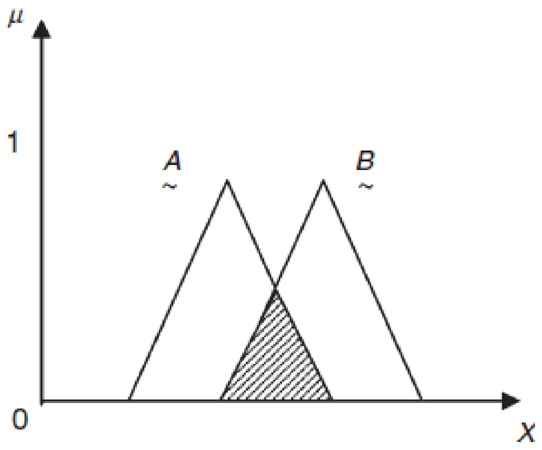


Figure 3.3: A AND B

3.2.3 Complement

The membership function of the Complement of a Fuzzy set A with membership function μ_A is defined as the negation of the specified membership function. This is called the *negation* criterion.

$$\mu_{\bar{A}} = 1 - \mu_A \qquad (3.3)$$

The Complement operation in Fuzzy set theory as shown in figure 3.4 is the equivalent of the **NOT** operation in Boolean algebra.

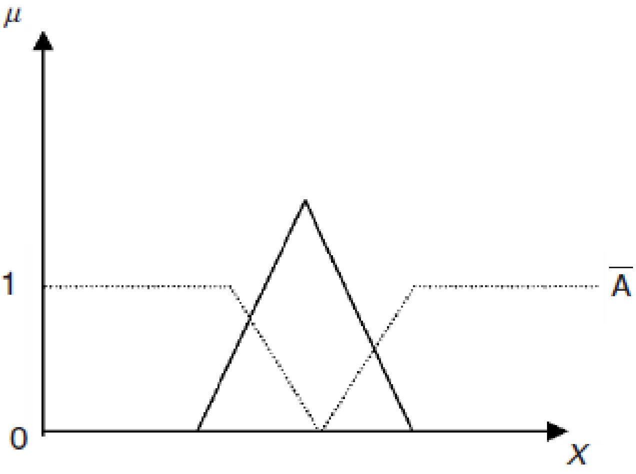


Figure 3.4: NOT A

Some properties of fuzzy set operations are given in Table 3.1[18] [19].

Table 3.1 Some Properties of Fuzzy Sets Operations

Law of contradiction	$A \cap \bar{A} = \emptyset$
Law of excluded middle	$A \cup \bar{A} = I$
De Morgan's laws	$\overline{(A \cap B)} = \bar{A} \cup \bar{B}$ $\overline{(A \cup B)} = \bar{A} \cap \bar{B}$
Involution (Double negation)	$\bar{\bar{A}} = A$
Commutative	$A \cap B = B \cap A$ $A \cup B = B \cup A$
Associative	$A \cap (B \cap C) = (A \cap B) \cap C$ $A \cup (B \cup C) = (A \cup B) \cup C$
Distributive	$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$ $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$

3.3 MEMBERSHIP FUNCTION

Unlike the aforementioned conventional set, a fuzzy set (Zadeh, 1965) expresses the degree to which an element belongs to a set. Hence the characteristic function of a fuzzy set is allowed to have values between 0 and 1, which denotes the degree of membership of an element in a given set.

If X is a collection of objects denoted generically by x, then a "fuzzy set" A in X is defined as a set of ordered pairs [18]:

$$A = \{(x, \mu_A(x)) \mid x \in X\} \qquad (3.4)$$

where $\mu_A(x)$ is called "membership function" (or MF for short) for the fuzzy set A. The MF maps each element of X to a membership grade (or membership value) between 0 and 1 as shown in Figure 3.5.

Obviously, the definition of a fuzzy set is a simple extension of the definition of a classical set in which the characteristic function is permitted to have any values between 0 and 1. If the values of the membership function are restricted to either 0 or 1, then A is reduced to a classical set and $\mu_A(x)$ is the characteristic function of A [18].

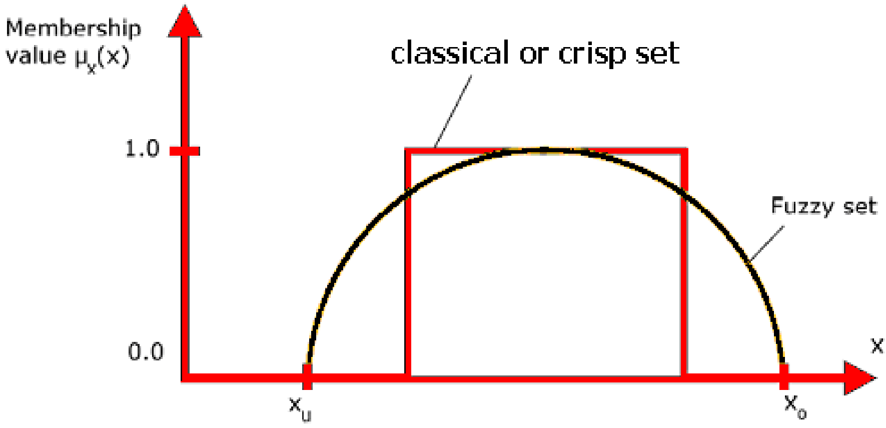


Figure 3.5: Membership Value in Fuzzy Set

3.3.1 Features of Membership Function

Features of Membership Function as shown in Figure 3.6 divided to [20]:

1- Support

The "support" of a fuzzy set A is the set of all points x in X such that $\mu_A(x) > 0$:

$$support\ (A) = \{ x \mid \mu_A(x) > 0 \} \qquad (3.5)$$

2- Core:

The "core" of a fuzzy set is the set of all points x in X such that $\mu_A(x) = 1$:

$$core\ (A) = \{ x \mid \mu_A(x) = 1 \} \qquad (3.6)$$

3- Crossover points

A "crossover point" of a fuzzy set A is a point $x \in X$ at which $\mu_A(x) = 0.5$:

$$crossover\ (A) = \{ x \mid \mu_A(x) = 0.5 \} \qquad (3.7)$$

4- Boundaries:

Comprise the elements x of the universe $0 < \mu_A(x) < 1$

5-α-cut:

The "α-cut" or "α-level set" of a fuzzy set A is a crisp set defined by

$$A\alpha = \{ x \mid \mu_A(x) \geq \alpha \} \qquad (3.8)$$

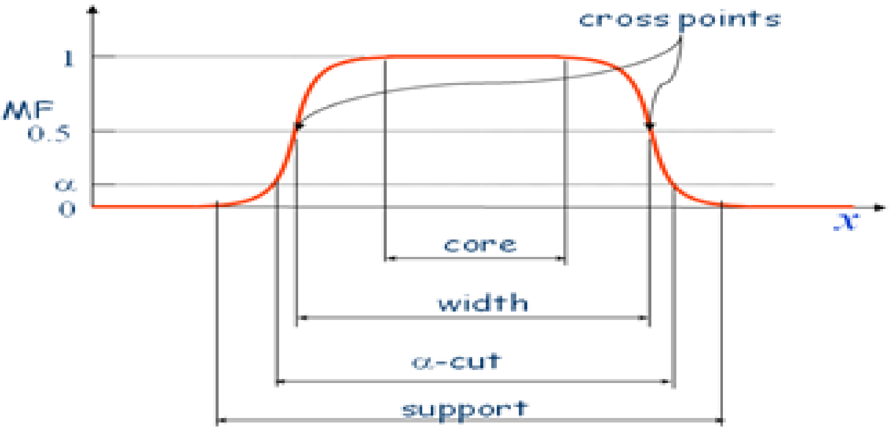


Figure 3.6: MF Terminology

3.3.2 Types of Membership Function

In the classical sets there is one type of membership function but in fuzzy sets there are many different types of membership function, now will show some of these types [20].

1- Triangular MFs

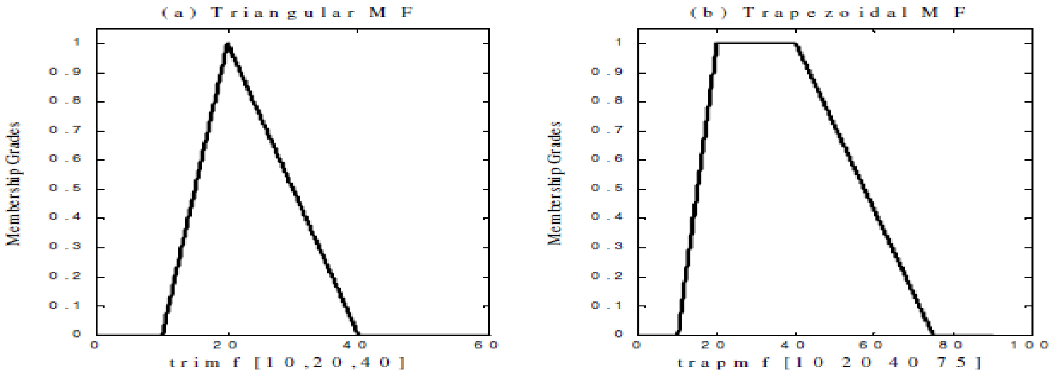
A "triangular MF" as shown in Figure 3.7(a) is specified by three parameters {a, b, c} as follows:

$$y = triangle(x; a, b, c) = \begin{cases} 0, & x \le a. \\ \dfrac{x-a}{b-a}, & a \le x \le b. \\ \dfrac{c-x}{c-b}, & b \le x \le c. \\ 0, & c \le x. \end{cases} \qquad (3.9)$$

2- Trapezoidal MFs

A "trapezoidal MF" as shown in Figure 3.7(b) is specified by four parameters {a, b, c, d} as follows:

$$\mathrm{trapezoid}(\mathrm{x}; \mathrm{a}, \mathrm{b}, \mathrm{c}, \mathrm{d}) = \begin{cases} 0, & \mathrm{x} \le \mathrm{a}. \\ \dfrac{\mathrm{x}-\mathrm{a}}{\mathrm{b}-\mathrm{a}}, & \mathrm{a} \le \mathrm{x} \le \mathrm{b}. \\ 1, & \mathrm{b} \le \mathrm{x} \le \mathrm{c}. \\ \dfrac{\mathrm{d}-\mathrm{x}}{\mathrm{d}-\mathrm{c}}, & \mathrm{c} \le \mathrm{x} \le \mathrm{d}. \\ 0, & \mathrm{d} \le \mathrm{x}. \end{cases} \qquad (3.10)$$



(a)Triangular MF **(b)Trapezoidal MF**

Figure 3.7: Examples of Two Types of Parameterized MFs

3- Gaussian MFs

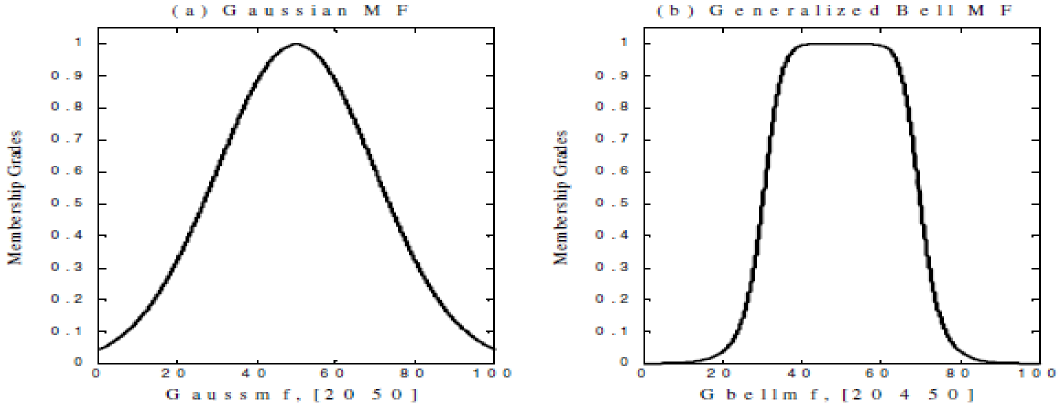
A "Gaussian MF" as shown in Figure 3.8(a) is specified by two parameters $\{c, \sigma\}$:

$$\text{gaussian}\ (x;\ c\,,\sigma) = e^{2^{\frac{-1(x-c)}{\sigma}}} \qquad (3.11)$$

4- Generalized bell MFs

A "generalized bell" as shown in Figure 3.8(b) is specified by three parameters $\{a, b, c\}$:

$$bell(x; a, b, c) = \frac{1}{1 + 1(x-c)/a|^{2b}} \qquad (3.12)$$



(a)Gaussian **(b) Generalized Bell**

Figure 3.8: Examples of Two Classes of Parameterized Continuous MFs

5- Sigmoidal MFs

A "Sigmoidal MF" as shown in Figure 3.9 is defined by the following equation:

$$sig(x;a,c)=\frac{1}{1+exp\,[-a(x-c)]} \qquad (3.13)$$

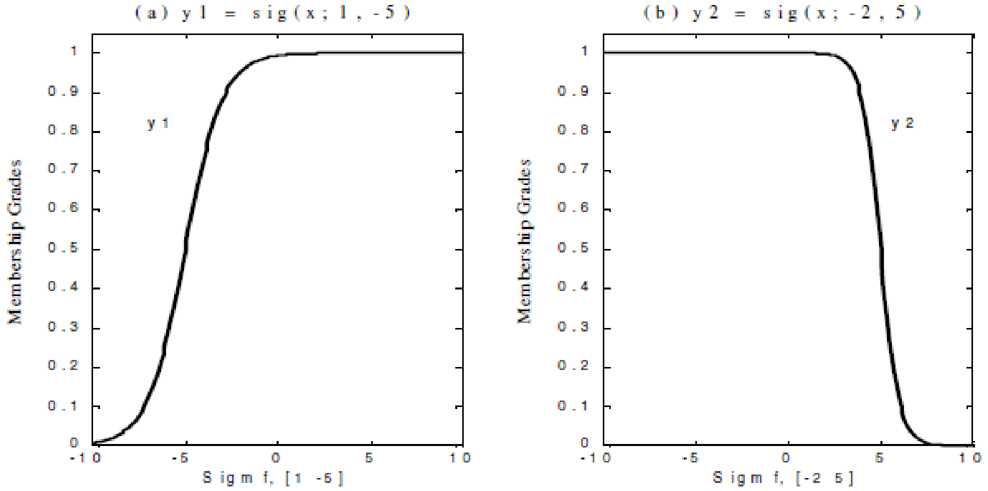


Figure 3.9: Two Sigmoidal Functions

3.4 GENERAL STRUCTURE OF "FLC" SYSTEM

The basic parts of every fuzzy controller are displayed in Figure 3.10. The fuzzy logic controller (FLC) is composed of a fuzzification interface, knowledge base, inference engine, and defuzzification interface.

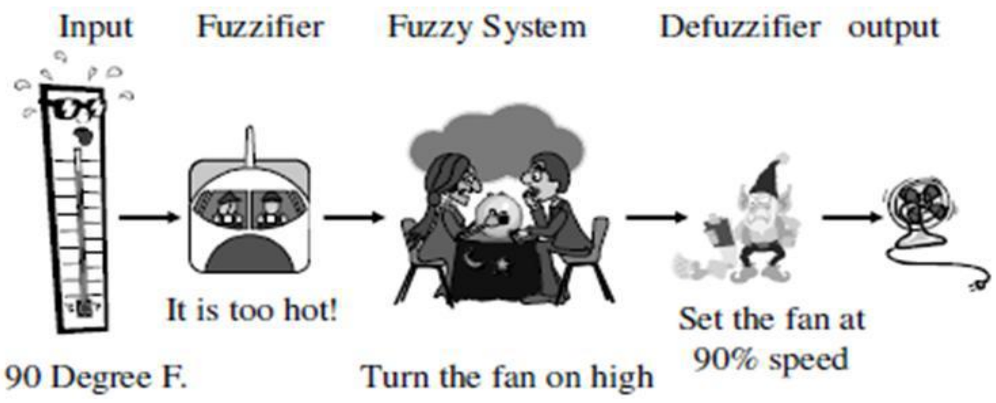


Figure 3.10: General Structure of Fuzzy Systems

3.4.1 Fuzzification

The first step in fuzzy logic processing the crisp inputs is transformed into fuzzy inputs as shown in Figure 3.11. This transformation is called fuzzification. The system must turn numeric values into language and corresponding domains to allow the fuzzy inference engine to inference to transform crisp input into fuzzy input, membership functions must be first be defined for each input. Once membership functions are defined, fuzzification takes a real time input value, such as temperature, and compares it with the stored membership function information to produce fuzzy input values. Fuzzification plays an important role in dealing with uncertain information that might be objective in nature [21].

It converts the *crisp input* to a *linguistic variable* using the membership functions stored in the fuzzy knowledge base.

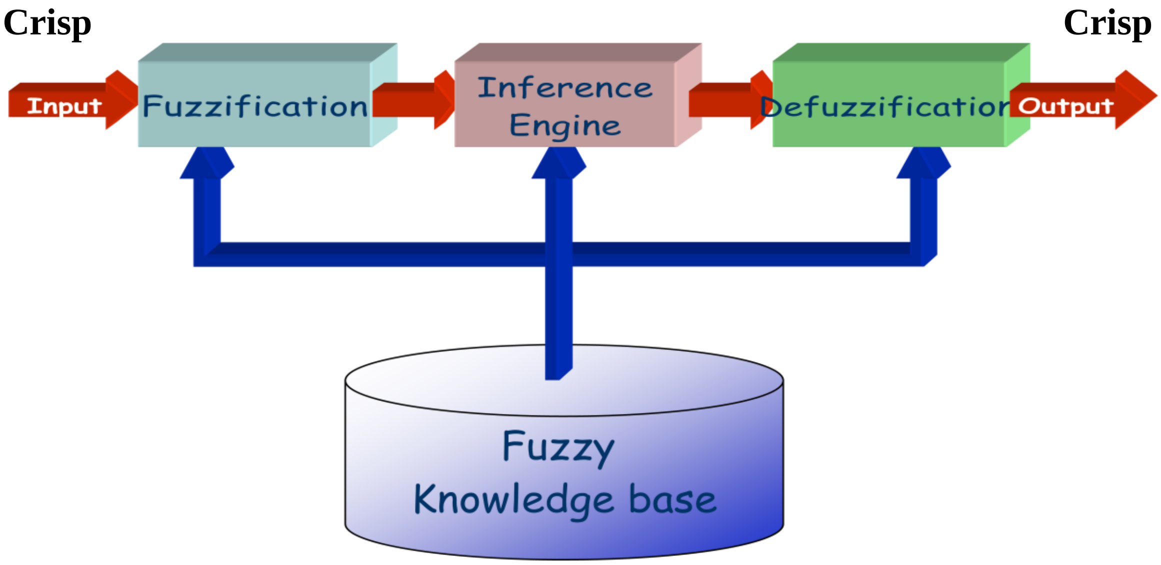


Figure 3.11: Basic Parts of Fuzzy Logic Controller

3.4.2 Knowledge Base

Knowledge base is the inference basis for fuzzy control. It defines all relevant language control rules and parameters. The knowledge base is the core of a fuzzy control system.

The knowledge base of Fuzzy Logic Controller (FLC) is comprised of two parts [22]:

1. Database.

2. Rule base

A linguistic controller contains rules in the (if-then) format. The Rule base is the cornerstone of the fuzzy model. The expert knowledge, which is assumed to be given as a number of if-then rules, is stored in a fuzzy rule base. The rules may use several variables in both the condition and the conclusion of the rules.

- **Linguistic Variables**

A "Linguistic variable" is characterized by a quintuple $(x, T(x), X, G, M)$ in which x is the name of the variable; $T(x)$ is the "term set" of x-that is, the set of its "linguistic values" or "linguistic terms"; X is the universe of discourse, G is a "syntactic rule" which generates the terms in $T(x)$; and M is a "semantic rule" which associates with each linguistic value A its meaning $M(A)$, where $M(A)$ denotes a fuzzy set in X[20].

- **Fuzzy Rules**

As was pointed out by Zadeh in his work on this area (Zadeh, 1973), conventional techniques for system analysis are intrinsically unsuited for dealing with humanistic systems, whose behavior is strongly influenced by human judgment, perception, and emotions. This is a manifestation of what might be called the "principle of incompatibility"[20].

A "fuzzy if-then rule" (also known as “fuzzy rule”, “fuzzy implication” or "fuzzy conditional statement") assumes the form

$$\boldsymbol{If}\ x\ is\ A\ \boldsymbol{then}\ y\ is\ B \qquad (3.14)$$

where A and B are linguistic values defined by fuzzy sets on universes of discourse X and Y, respectively. Often "x is A" is called "antecedent" or "premise", while "y is B" is called the "consequence" or "conclusion".

Examples of fuzzy if-then rules are widespread in our daily linguistic expressions, such as the following:

- If pressure is high, then volume is small.
- If the road is slippery, then driving is dangerous.
- If the speed is high, then apply the brake a little.

3.4.3 Fuzzy Inference Systems

There are many inference methods, which deals with fuzzy inference like: Mamdani method, Larsen method, Tsukamoto method, and the Sugeno style inference, or, Takagi-Sugeno_Kang (TSK) method. The most important and widely used in fuzzy controllers are the Mamdani and Takagi-Sugeno methods.

3.4.3.1 Mamdani method

Mamdani method is the most commonly used fuzzy inference technique. In 1974, Professor Ebrahim Mamdani of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators. The Mamdani-style fuzzy inference process is performed in four steps [20]:

1) Fuzzification of the input variables

2) Rule evaluation.

3) Aggregation of the rule outputs

4) Defuzzification

To illustrate the fuzzy inference let's examine a simple two-input one-output problem that includes three rules:

Rule (1) …. IF X is A3 OR Y is B1 THEN z is C1

Rule (2)…. IF X is A2 AND Y is B2 THEN z is C2

Rule (3)…. IF X is A1 THEN z is C3

Step 1: Fuzzification

The first step in the application of fuzzy reasoning is a Fuzzification of inputs in the controller, which is to take the crisp inputs, x1 and y1, and determine the degree to which these inputs belong to each of the appropriate fuzzy sets. It means that to every crisp value of input we attribute a set of degrees of membership (mj, j=1,n) to fuzzy sets defined in the universe of discourse for that input.

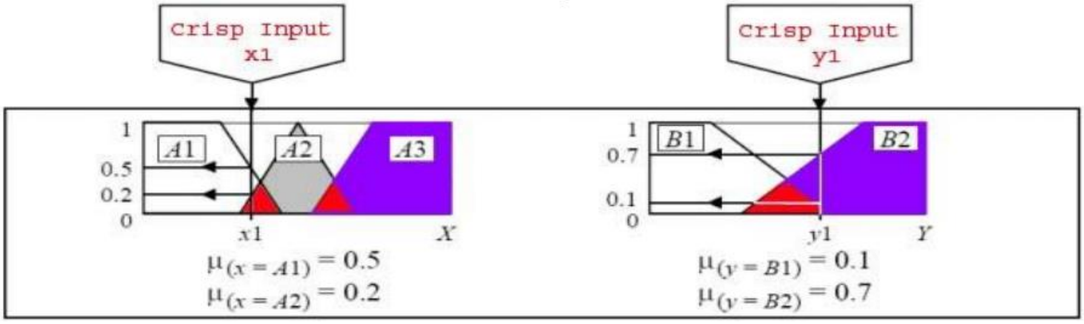


Figure 3.12:Fuzzification Stage

Step 2: Rule evaluation

The second step is to take the Fuzzified inputs, μ (x=A1) = 0.5, μ (x=A2) = 0.2 ،μ (y=B1) = 0.1 and μ (y=B2) = 0.7, and apply them to the antecedents of the fuzzy rules .If a given fuzzy rule has multiple antecedents, the fuzzy operator (AND or OR) is used to obtain a single number that represents the result of the antecedent evaluation. This number (the truth value) is then applied to the consequent membership function. To evaluate the disjunction of the rule antecedents, we use the OR fuzzy operation. As shown Operations with fuzzy sets the most used approach for the union is to get the maximum:

$\mu A\cup B(x) = \max [\mu A(x), \mu B(x)]$ ………………………………………… (3.15)

Similarly, in order to evaluate the conjunction of the rule antecedents, we apply the AND fuzzy operation intersection which used minimum approach:

$\mu A\cap B(x) = \min [\mu A(x), \mu B(x)]$ ……………………………….………... (3.16)

The rule evaluations are clearly appears in Figure (3.13)

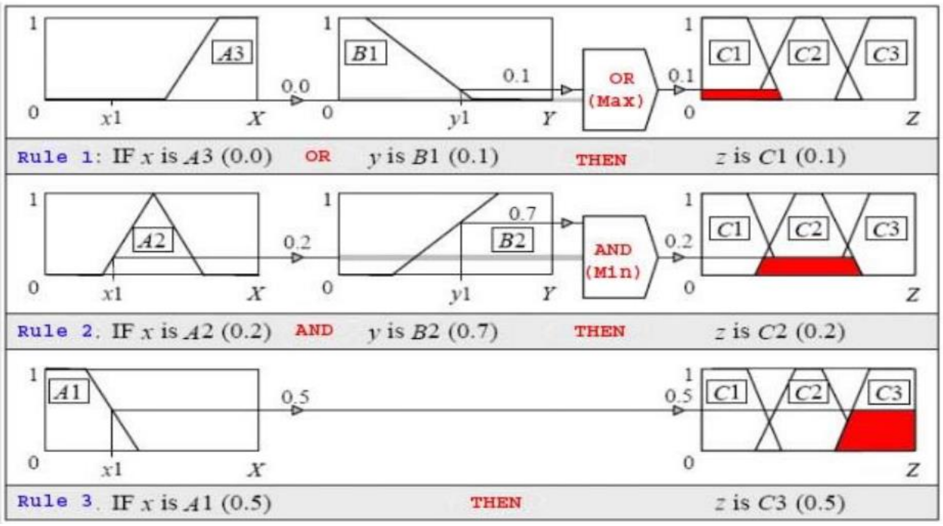


Figure 3.13: Rule Evaluation in Mamdani Method

The most common method of correlating the rule consequent with the truth value of the rule antecedent is to cut the consequent membership function at the level of the antecedent truth. This method is called clipping. Since the top of the membership function is sliced, the clipped fuzzy set loses some information. However, clipping is still often preferred because it involves less complex and faster mathematics, and generates an aggregated output surface that is easier to Defuzzify.

Step 3: Aggregation of the rule outputs

Aggregation is the process of unification of the outputs of all rules. We take the membership functions of all rule consequents previously clipped (Max Min Composition) or scaled (Max-Product Composition) and combine them into a single fuzzy set.

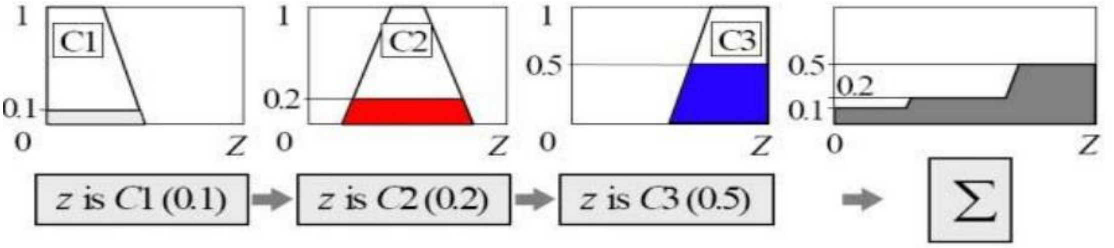


Figure 3.14: Aggregation Stage in Mamdani Method

Step 4: Defuzzification

Defuzzify the aggregate output fuzzy set into a single number. This step will explainin details in section 3.5.4. But in this example we used the COG method to solve the defuzzification as shown in Figure 3.15

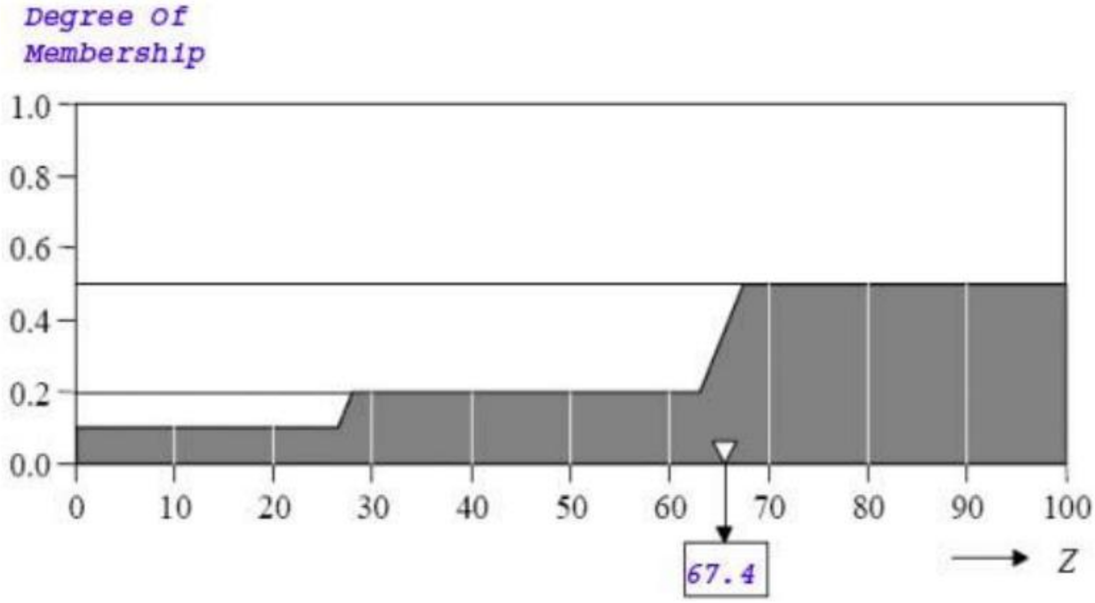


Figure 3.15: COG Approach in Defuzzification Stage

3.4.3.2 Sugeno method

Since Mamdani's pioneering works on fuzzy control motivated by Zadeh's approach to inexact, there have been numerous studies on fuzzy reasoning. Most fuzzy controllers have been designed, based on human operator experience and/or control engineer knowledge. It is however often the case that an operator cannot tell linguistically what kind of action he takes in a particular situation. In this respect, it is quite useful to provide a method of modeling the control actions using numerical data. In 1985 Takagi-Sugeno-Kang suggested to use a single spike, a singleton, as the membership function of the rule consequent, and they suggested another approach that using equation consequent in place off singleton consequent. A singleton, or more precisely a fuzzy singleton, is a fuzzy set with a membership function that is unity at a single particular point on the universe of discourse and zero everywhere else. Sugeno-style fuzzy inference is very similar to the Mamdani method. Sugeno changed only a rule consequent. Instead of a fuzzy set, he used a mathematical function of the input variable[20].

The format of the Sugeno-style fuzzy rule is:

IF X is A AND Y is B THEN Z is f (x, y) ………………………………. (3.17)

Where X, Y and Z are linguistic variables; A and B are fuzzy sets on universe of discourses X and Y, respectively; and f (x, y) is a mathematical function. The most commonly used zero-order Sugeno fuzzy model applies fuzzy rules in the following form:

IF X is A AND Y is B THEN Z is k ……………………………….……. (3.18)

Where k is constant.

In this case, the output of each fuzzy rule is constant. All consequent membership functions are represented by singleton spikes. The following Figures (3.16, 3.17, and 3.18) illustrate the idea for TSK which likes Mamadni steps.

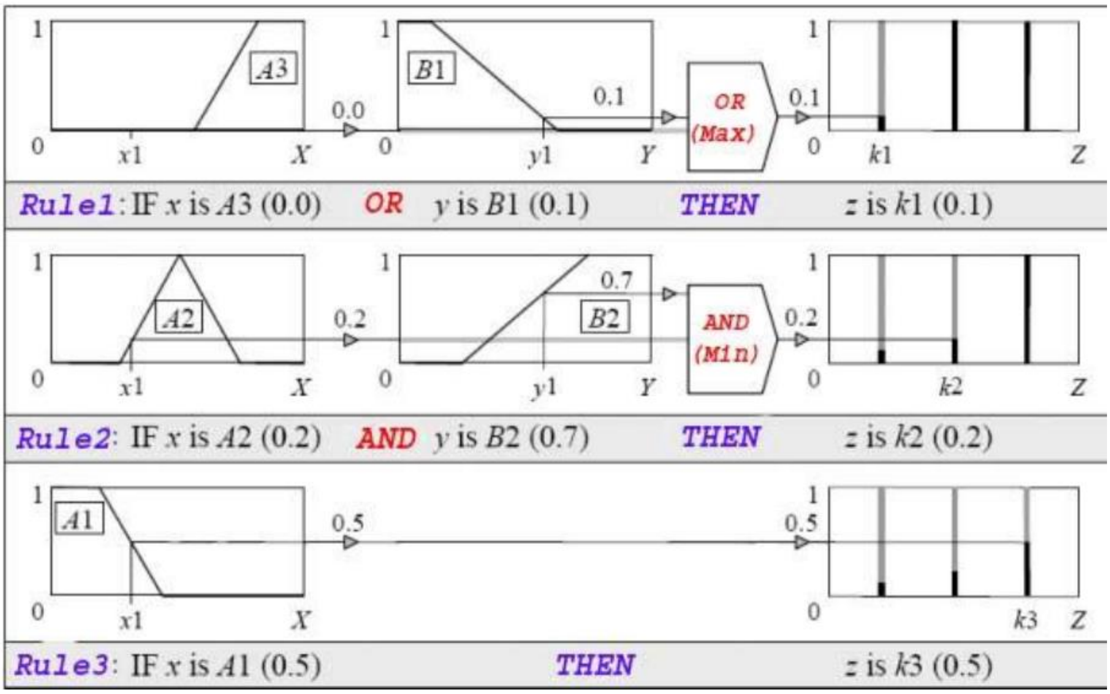


Figure 3.16: Rule Evaluation Stage in TSK Method

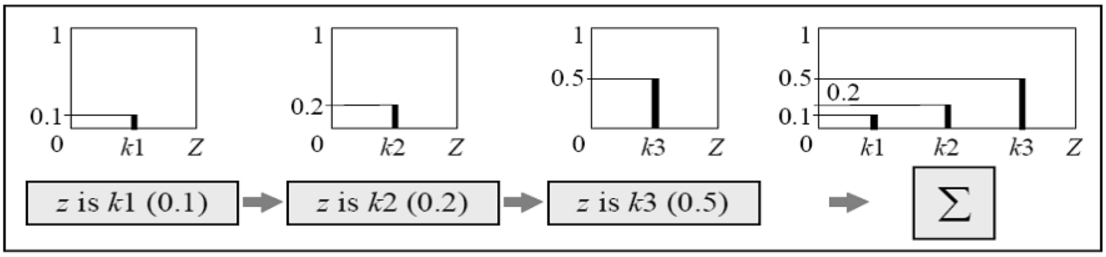


Figure 3.17: Aggregation Stage in TSK Method.

For Defuzzification stage it's better to use Weighted Average method (WA):

$$WA = \frac{\mu(k1) \times k1 + \mu(k2) \times k2 + \mu(k3) \times k3}{\mu(k1) + \mu(k2) + \mu(k3)} = \frac{0.1 \times 20 + 0.2 \times 50 + 0.5 \times 80}{0.1 + 0.2 + 0.5} = 65$$

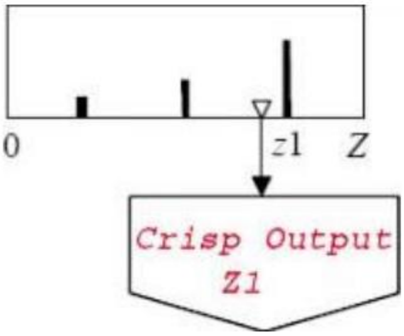


Figure 3.18: (WA) Method in Defuzzification Stage.

The overall fuzzy logic controller "FLC" appear in Figure (3.19)

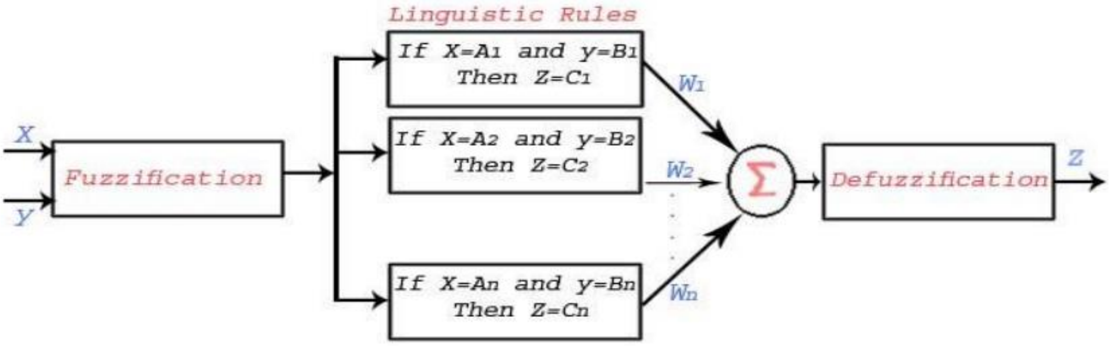


Figure 3.19: General Structure of Fuzzy Logic Control Part of The System

3.4.4 Defuzzification

Defuzzification refers to the way a numeric value is extracted from a fuzzy set as a representative value. In general, there are five methods for defuzzification. A brief explanation of each defuzzification strategy follows [20].

- **Centroid of area Z_{COA}:**

$$Z_{COA} = \frac{\int \mu_A(Z)ZdZ}{\mu_A(Z)dZ} \qquad (3.19)$$

where $\mu_A(z)$ is the aggregated output MF. This is the most widely adopted defuzzification strategy, which is reminiscent of the calculation of expected values of probability distributions. Various defuzzification methods are illustrated in figure 3.14.

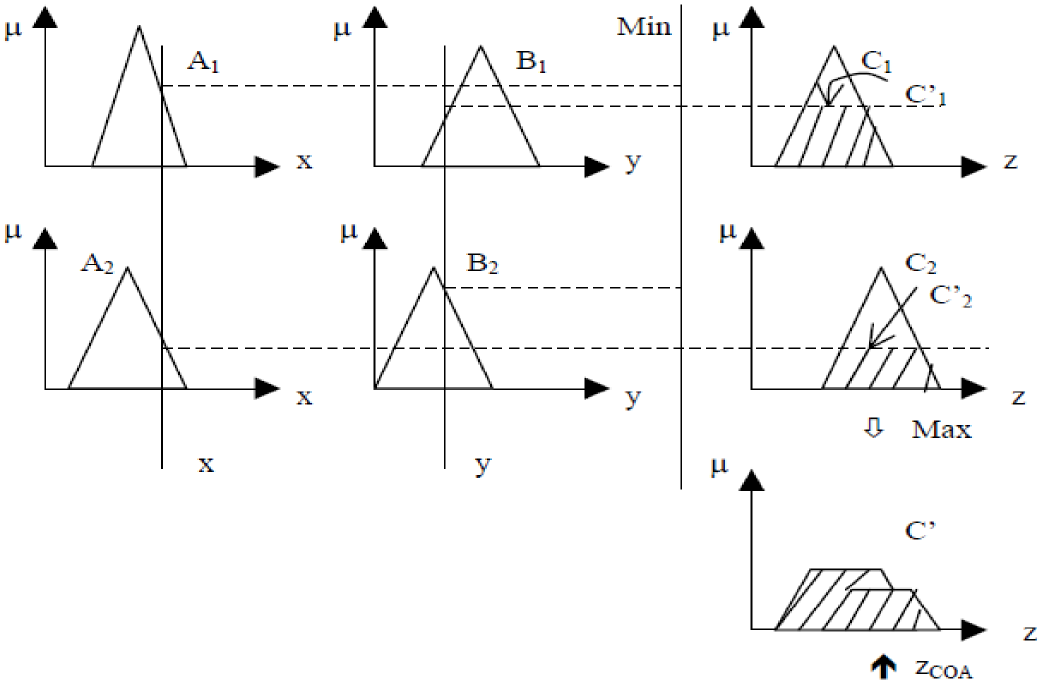


Figure 3.20: Mamdani Fuzzy Inference System using the Min and Max Operators

- **Bisector of area Z_{BOA} :**

$$\int_{\alpha}^{Z_{BOA}} \mu_A(Z)dZ = \int_{Z_{BOA}}^{\beta} \mu_A(Z)dZ \qquad (3.20)$$

where $\alpha = min\{z \mid z \in Z\}$ and $\beta = max\{z \mid z \in Z\}$.

- **Mean of maximum Z_{MOM}:** is the average of the maximizing z at which the MF reaches a maximum $\mu *$. Mathematically,

$$Z_{MOM} = \frac{\int ZdZ}{\int dZ} \tag{3.21}$$

- **Smallest of maximum Z_{SOM}**: is the minimum (in terms of magnitude) of the maximizing z.
- **Largest of maximum Z_{LOM}**: is the maximum (in terms of magnitude) of the maximizing z.

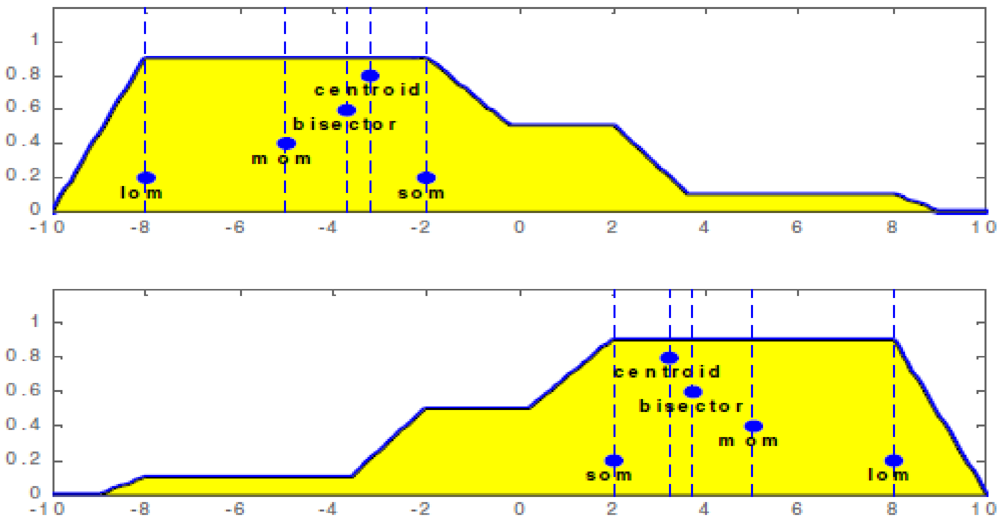


Figure 3.21: Various Defuzzification Methods for obtaining a Numeric Output

In this thesis the Mamdani model will be used and will have two inputs error and change of errors, and the output will be change of duty cycle. All inputs and output have seven membership functions. And the Z_{COA} defuzzification method will be used. The rule base will be as the next form:

IF error is zero AND change of error is zero THEN change of duty cycle is zero.

These rules are written by the experience.

3.4.5 Advantages And Disadvantages Of Two Methods

Advantages of the Mamdani Fuzzy method:

- It is intuitive and simple to build.
- It is widely used for second order systems with both linear and nonlinear characteristics.
- It has widespread acceptance.
- It is well suited to human feeling.

Disadvantages of the Mamdani Fuzzy method:

- It is only suited to the long delay system, such as the temperature control system, since it is too simple to control the process quickly.
- It needs additional device to improve the efficiency, when it controls the high frequent input system.

The advantages of Takagi-Sugeno Model:

- It is computationally efficient.
- It works well with linear techniques (e.g., PID control).
- It works well with optimization and adaptive techniques.
- It has guaranteed continuity of the output surface.
- It is well suited to mathematical analysis.
- It can optimize the parameters of the output to improve the efficiency.

Disadvantages of the Sugeno Fuzzy method:

- It is not intuitive.
- When using the higher order Sugeno method, it is complex.

How to make a decision Mamdani or Sugeno?

- Mamdani method is widely accepted for capturing expert knowledge. It allows us to describe the expertise in more intuitive, more human-like manner .However, Mamdani-type fuzzy inference entails a substantial computational burden.
- On the other hand, Sugeno method is computationally effective and works well with optimization and adaptive techniques, which makes it very attractive in control problems, particularly for dynamic nonlinear systems[23].

CHAPTER 4 DESIGNING FUZZY CONTROLLER BASED LCL RESONANT CONVERTER

4.1 OVERALL SYSTEM DESIGN

This chapter presents the process used to design fuzzy controllers based LCL resonant converter. Also the stability analysis has been provided to support the selection of Fuzzy controller for the LCL resonant converter, using Try and error method to improve the settling time, steady state error and the ripples of the output voltage of the system. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems are different in their outputs.

4.2 FUZZY BASED LCL RESONANT CONVERTER

The block diagram of LCL RC is shown in Figure 4.1. Unlike the conventional RC that has only three elements, the proposed resonant tank has one reactive energy storage element and two inductors elements that can change in current (LCL). The first stage converts a dc voltage to a high-frequency ac voltage. The second stage converts the ac power to dc power by a suitable high-frequency rectifier and a filter circuit. Power from the resonant circuit is taken either through a transformer in series with the resonant circuit or in parallel with the capacitor comprising the resonant circuit. In both cases, the high-frequency feature of the link allows the use of a high-frequency transformer to provide voltage transformation and ohmic isolation between the dc source and the load[14].

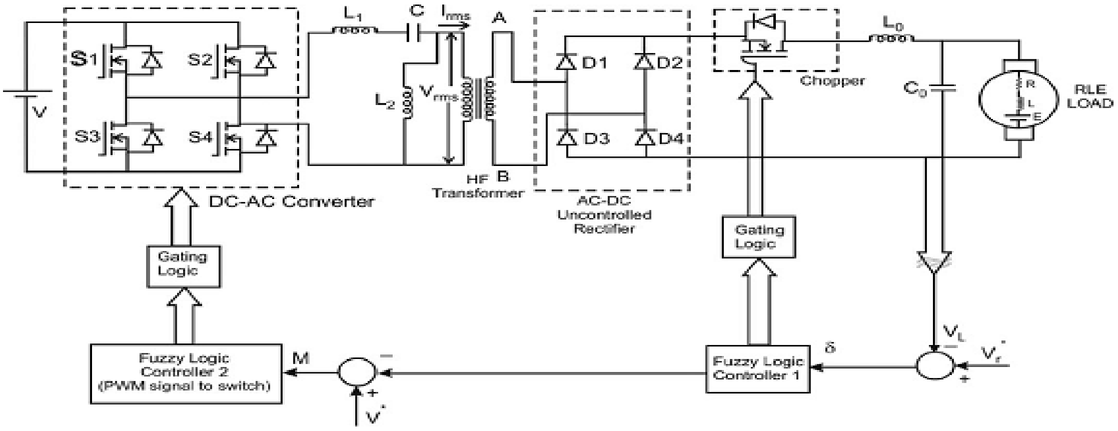


Figure 4.1: Block diagram of proposed LCL RC.

In an LCL RC, voltage of the load can be controlled by the chopper. The phase-domain control scheme is suitable for a wide variation of load condition because the output voltage is independent of load. The absence of dc current in the primary side of the transformer does not necessitate the requirement of current balancing. Another advantage of this circuit is that the reference currents are proportional to load current. This increases the efficiency of the converter at light loads because there is the reduction in device losses.

The filter circuit has some disadvantage. It is a capacitor input filter and it can be carried the large ripple current. It may be as much as 48% of the load current. The disadvantage is more severe for large output current with low voltage. Therefore, this circuit is suitable for high voltage low current regulators.

The resonant circuit consists of a series inductance L1, a parallel capacitor C, and a series inductance L2. S1–S4 is switching devices having base/gate turn-on and turn-off capabilities. The gate pulses for S1 and S4 are in phase but are at 180◦ out of phase with respect to the gate pulses for S2 and S3. The positive portion of the current flows through the MOSFET switch while the negative portion flows through the antiparallel diode. The load resistive or inductive or capacitive or RLE is connected across bridge rectifier via chopper, L0 and C0. The voltage across the points A and B is rectified and fed to a chopper circuit. Load is connected through L0 and C0. In the analysis that follows, it is assumed that the converter operates in the continuous conduction mode and the semiconductors have ideal characteristics.

4.2.1 Pulse Width Modulation (PWM)

PWM signals are pulse trains with fixed frequency and magnitude and variable pulse width. However, the width of the pulses (duty cycle) changes from pulse to pulse according to a modulating signal as illustrated in **Figure 4.2.** When a PWM signal is applied to the gate of the power transistor, it causes turn on and off intervals of the transistor to change from one PWM period to another according to the same modulating signal [21].

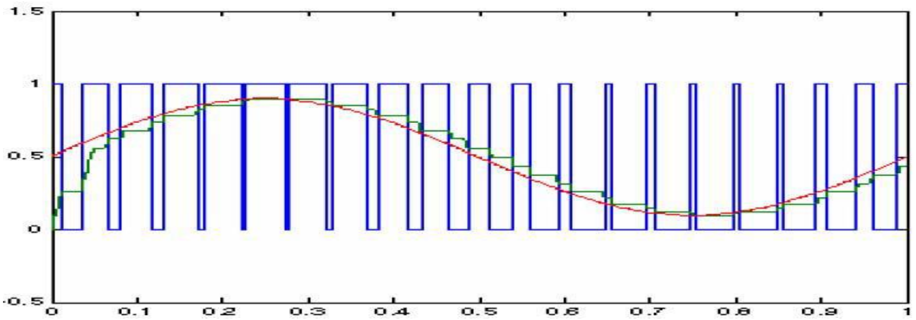


Figure 4.2: Pulse Width Modulation Waveforms[21]

4.2.2 Design of Fuzzy Logic Controller

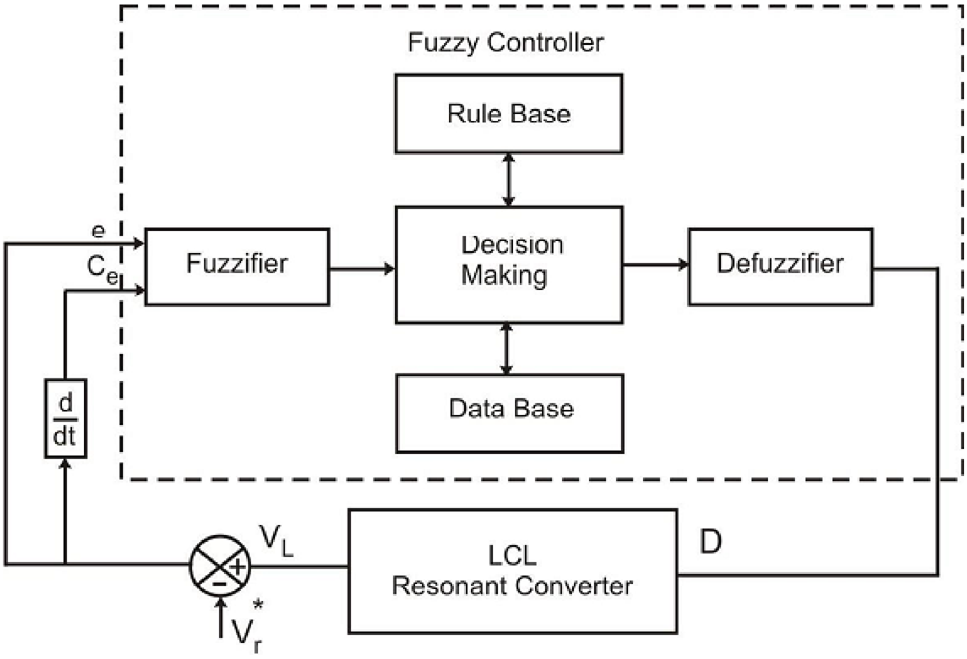


Figure 4.3:Block diagram of fuzzy control scheme for LCL RC

Fuzzy control involves three stages: fuzzification, inference or rule evaluation and defuzzification as shown in Figure 4.3. Fuzzy Logic Controller (FLC) provides an adaptive control for better system performance .Fuzzy logic is aims to provide solution for controlling non-linear processes and to handle ambiguous and uncertain situations. Fuzzy control is based on the fundamentals of fuzzy sets. The fuzzy control for the chosen SPRC is developed using input membership functions for error ‘e’ and change in error Ce’ and the output membership function for D, the duty ratio of converter .The fuzzy control scheme is implemented in this DC to DC converter and the results were recorded. The output of the fuzzy control algorithm is the change in duty cycle [d (k)].The duty cycle d (k) at the kth sampling time, is determined by adding the previous duty cycle [d (k-1)] to the calculated change in duty cycle.

$$d(k) = d(k-1) + d(k) \qquad (4.1)$$

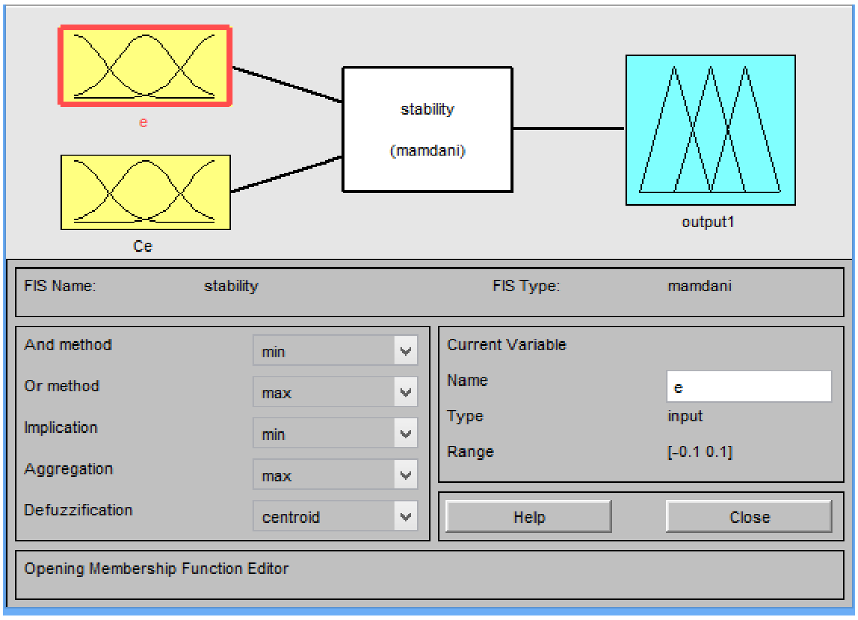
4.3 SIMULINK MODEL OF FUZZY BASED LCLRC

4.3.1 Fuzzy Logic Control (FLC)

LCL is modeled using MATLAB software. Fuzzy control is developed using the fuzzy toolbox. The fuzzy variables ‘e’, ‘Ce’ and ’D’ are described by triangular membership functions. Seven triangular membership functions are chosen in Table 5.1 shows the fuzzy rule base created in the present work based on intuitive reasoning and experience. Fuzzy memberships NB, NM,NS, ZE, PS,PM, PB are defined as negative big, negative medium, negative small, zero and positive small, positive medium and positive big respectively.

4.3.2 Rule Table and Inference Engine

Figure 4.4 shows The fuzzy logic control for LCL resonant converter is made from two inputs and one output variable, the error and change of error are as an input variables, while the change of duty cycle is output variable. And the Figure 4.5 shows fuzzy membership functions used for LCL resonant converter. The control rules that relate the fuzzy output to the fuzzy inputs are derived from general knowledge of the system behavior, perception and experience. The rule base for the designed fuzzy controller is given in the Table 4.1.



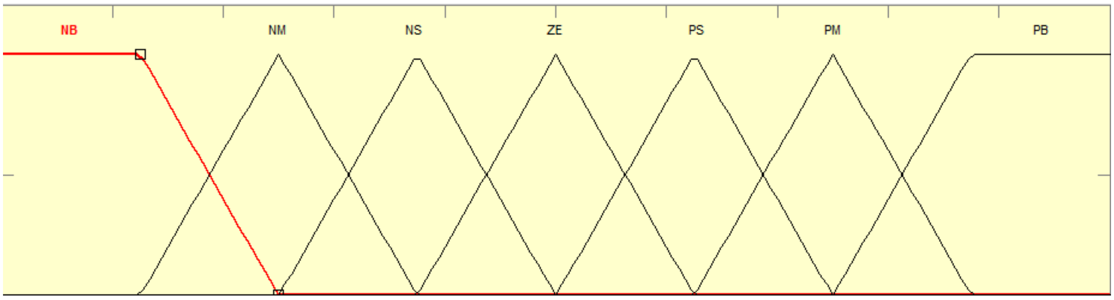
FIS Name: stability
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

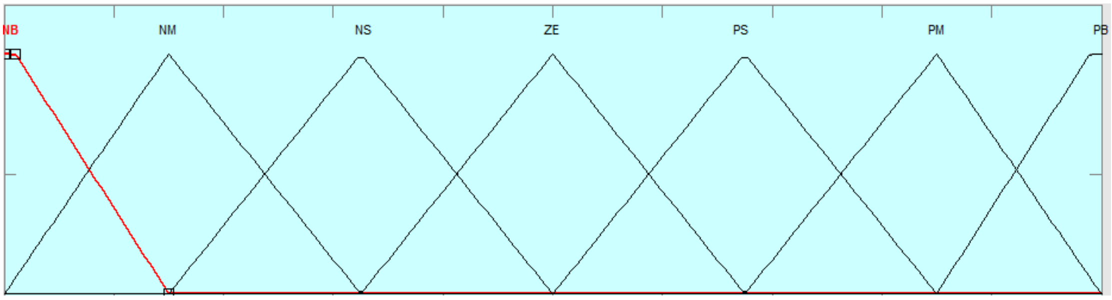
Current Variable
Name: e
Type: input
Range: [-0.1 0.1]

Opening Membership Function Editor

Figure 4.4:The Editor of Fuzzy Inference System using Matlab



Membership Function of Input Variable ‘error’ and ‘change of error’



Membership function for Output (D)

Figure 4.5:Fuzzy membership functions used for LCL resonant converter

Table 4.1 Fuzzy rule base

		ERROE						
		NB	NM	NS	Z	PS	PM	PB
CHANGE ERROR	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

Figure 4.6 shows the surface of fuzzy controller using the previous rules. Surface shows the relation between the inputs and output at any point in the intervals [-0.1 0.1] using the Centroid defuzzification method

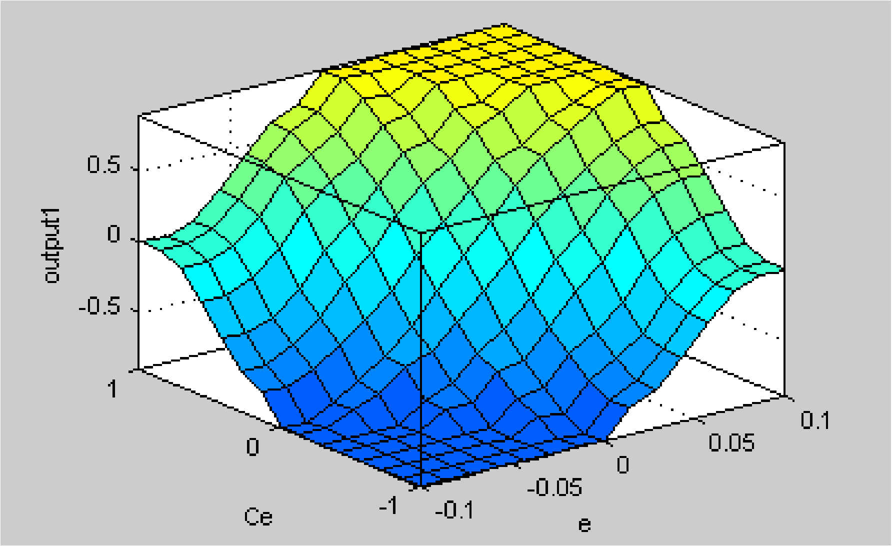


Figure 4.6: Surface of Fuzzy Controller

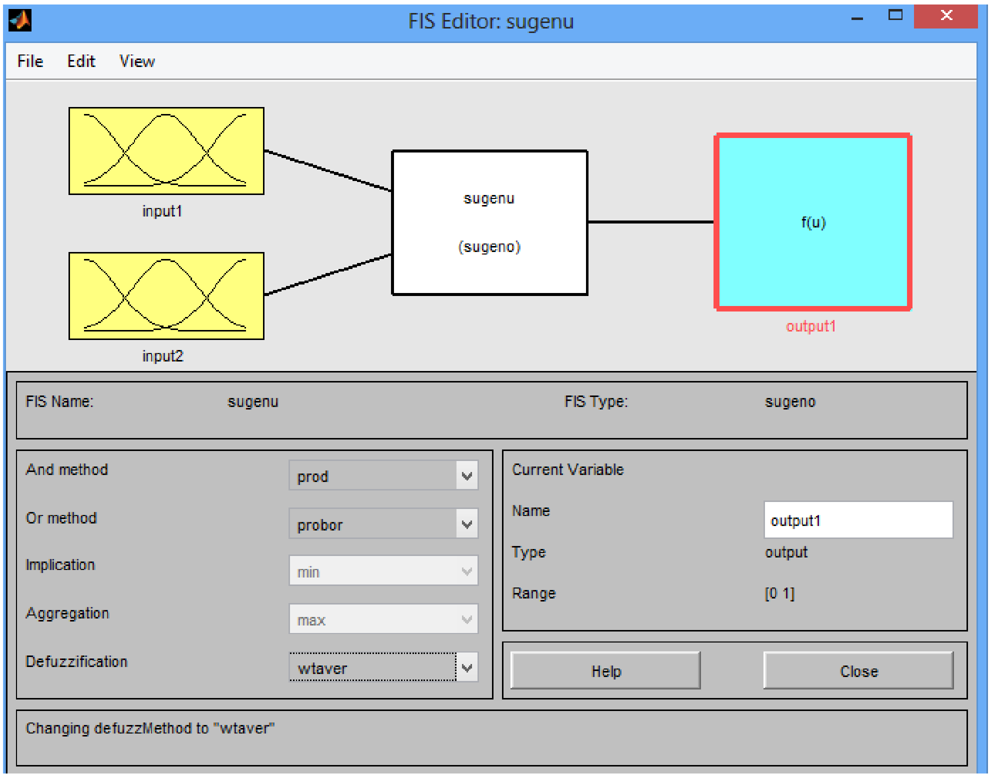
The rule firing contains the following steps:

(1) From the membership functions of the input 1, the linguistic under whose range, the actual values is present is found. Also its decimal height Degree of Belief (DOB) is got.

(2) From the membership functions of input 2, the corresponding linguistic is also found along with the DOB.

(3) For these two inputs, the output linguistic is fetched from the rule base.

Figure 4.7 shows The fuzzy logic control (Sugeno) for LCL resonant converter is made from two inputs and one output variable, which are the error and change of error as an input variables like FLC (Mamdani) controller, while the change in the controller just in the output variable. Figure 4.8 shows fuzzy membership functions of the output variable used for LCL RC. Figure 4.9 shows the rule of FLC(Sugeno) controller.



FIS Name: sugenu

FIS Type: sugeno

And method: prod

Or method: probor

Implication: min

Aggregation: max

Defuzzification: wtaver

Current Variable

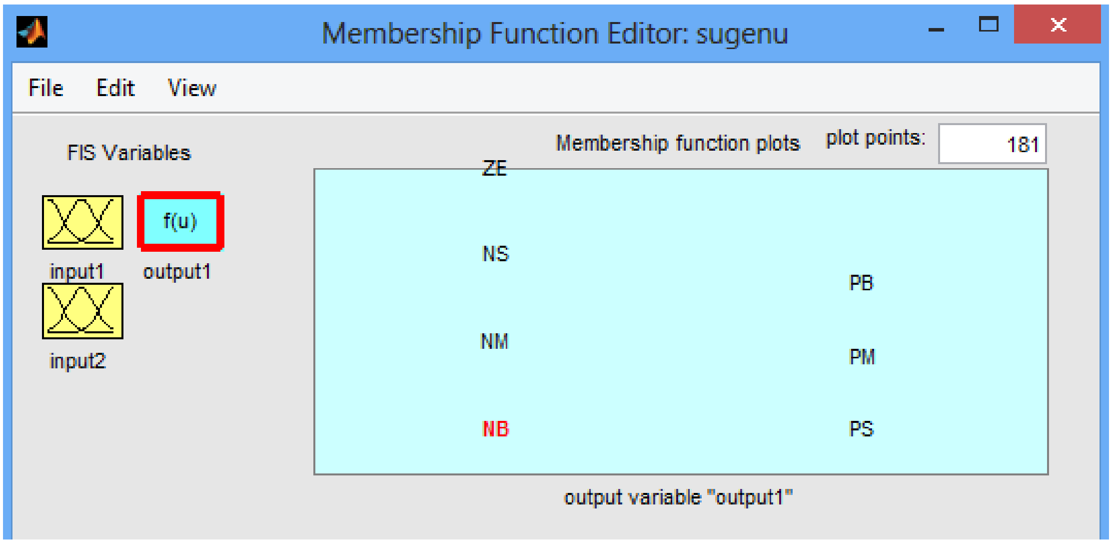
Name: output1

Type: output

Range: [0 1]

Changing defuzzMethod to "wtaver"

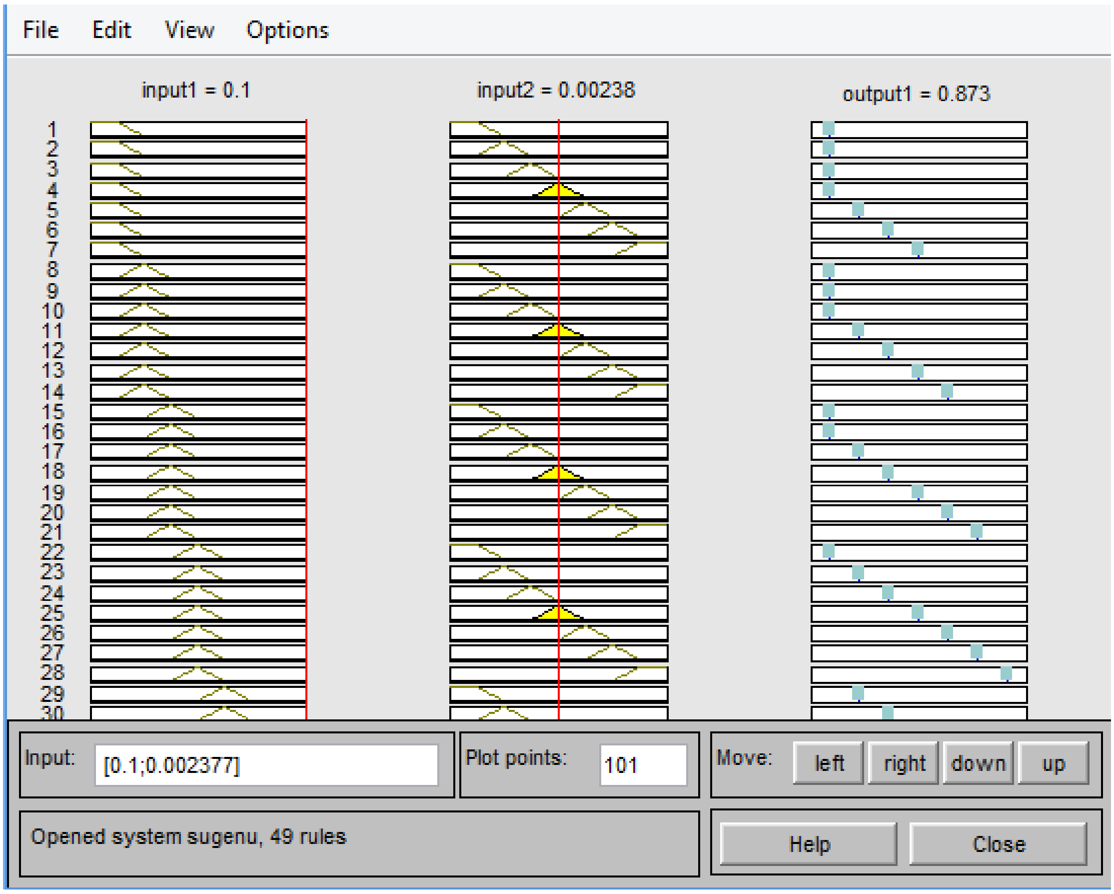
Figure 4.7:The Editor of Fuzzy(Sugeno) Inference System



plot points: 181

Figure 4.8:The output Membership function of Fuzzy(Sugeno) Inference System

The rule of the FLC(Sugeno)controller system for using the LCL RC where the range of the output variable as[-0.1,0.1] shows in Figure 4.9.



Input: [0.1;0.002377]

Plot points: 101

Opened system sugenu, 49 rules

Figure 4.9: The Rule Viewer of Fuzzy (sugenu) Inference System

4.3.3 Development of the FLC

At every sampling interval, the RMS values of the Sinusoidal reference voltage and load voltage are used to calculate the error(e) and change in error (Ce) signals that act as the input to the FLC. The stage of fuzzification, fuzzy inference and defuzzification are then performed by the program as generally described in the flowchart of Figure 4.10.

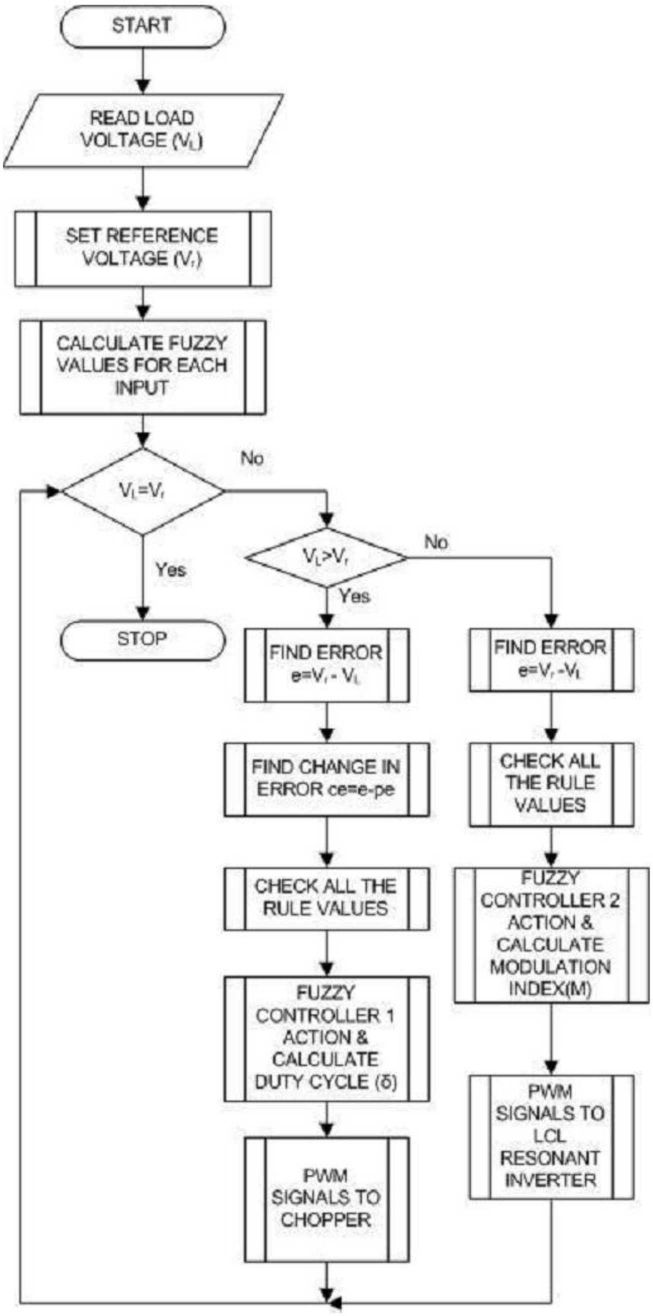


Figure 4.10: Flow chart

$$e = V_r - V_L \qquad (4.2)$$

$$C_e = e - P_e \qquad (4.3)$$

The closed loop simulation using FLC controller for the LCL RC is carried out using MATLAB/Simulink software. Depending on error and the change in error, the value of change of duty cycle is calculated. Set parameter instruction and function blocks available in MATLAB are used to update the new duty cycle of the pulse generators. The closed loop Simulink diagram of LCL Resonant Converter using FLC is shown in Figure 4.8. The entire system is simulated with a switching frequency of 50 KHz. The simulated converter output voltage Vo for a step change in load from 0.3 to 0.5 it's applied at 10 milliseconds. It is observed that the FLC for LCL regulates the output voltage with a settling time of 0.06 milliseconds.

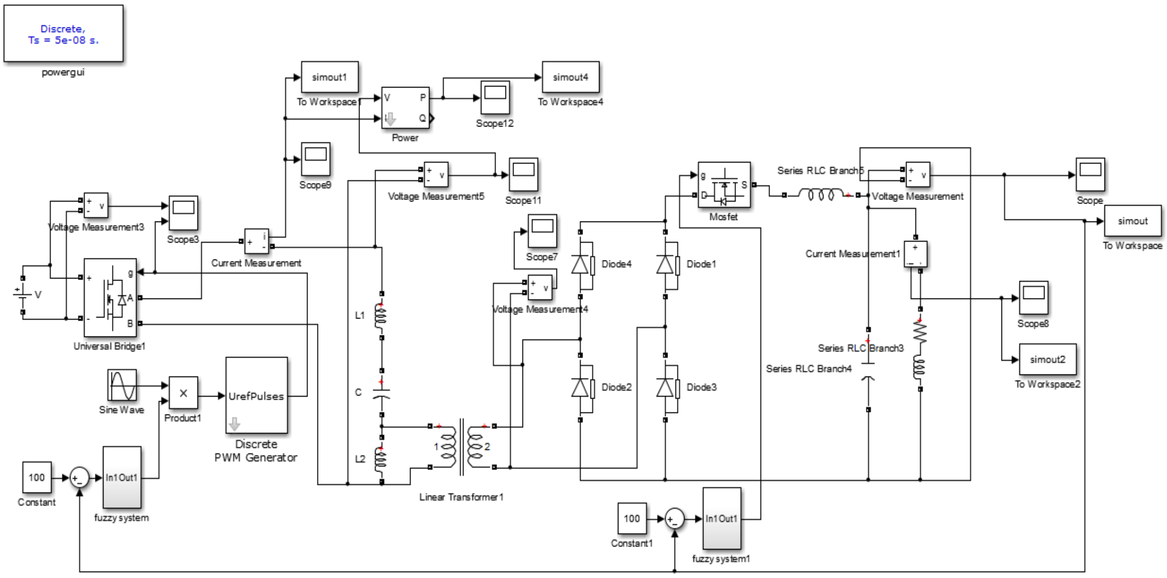


Figure 4.11: Simulink diagram of LCL resonant converter using FLC.

4.4 SIMULATION RESULTS

The proposed model has been simulated using MATLAB/Simulink toolbox.

The fuzzy controller has been designed for LCL RC. The FLC (Mamdani) performance and FLC (Sugeno) for the LCL RC is designed and compared with FLC for the LCL RC in reference[15].

4.5 Comparison Between thesis system and previous works

The result of applying the (FLC) Mamdani and FLC Sugeno to control the LCL RC is compared with FLC Closed Loop Response, in reference [15].

Figure (4.12-a, b, c), shows the effect of the three controllers

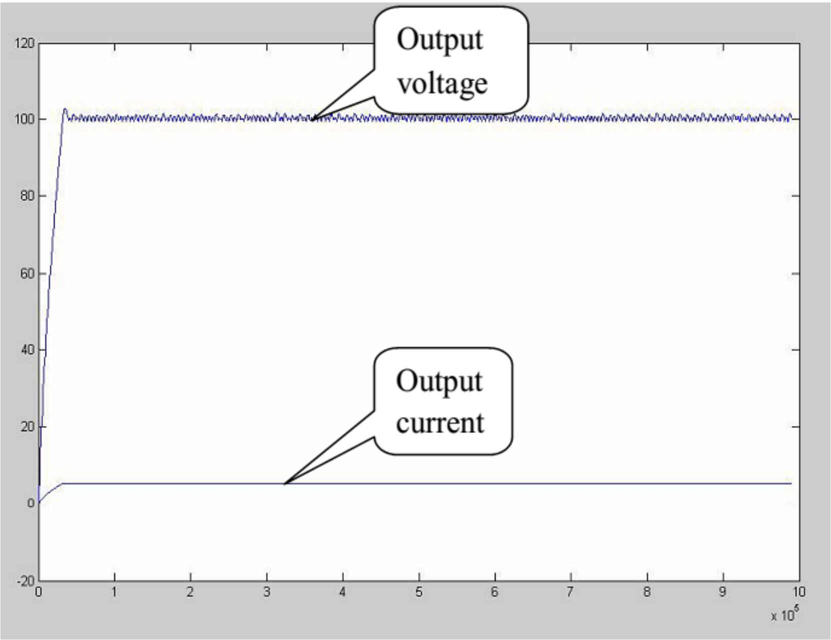


Figure 4.12-a: Simulated output voltage and current waveform with 100% load.[15]

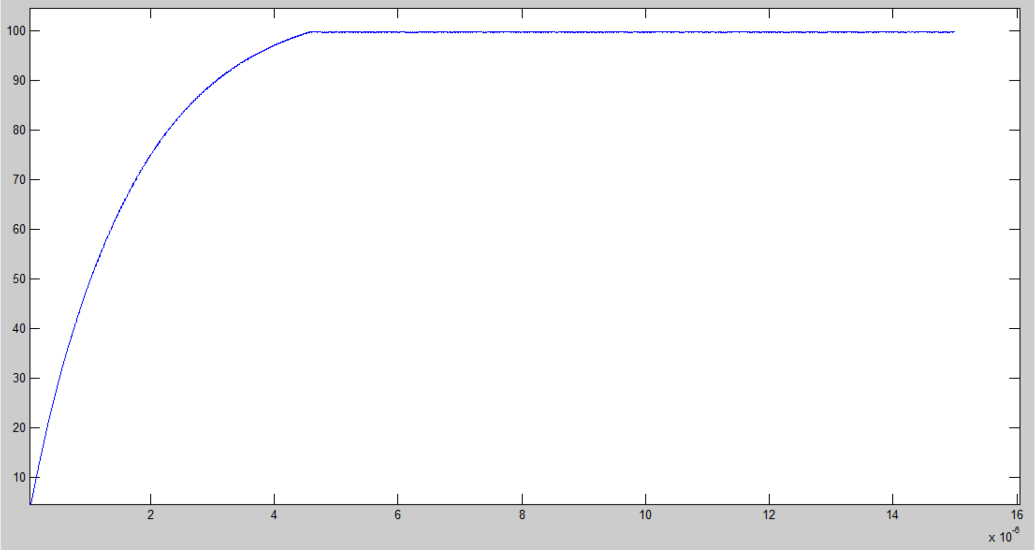


Figure 4.12-b: Simulated output voltage for FLC (Mamdani) system

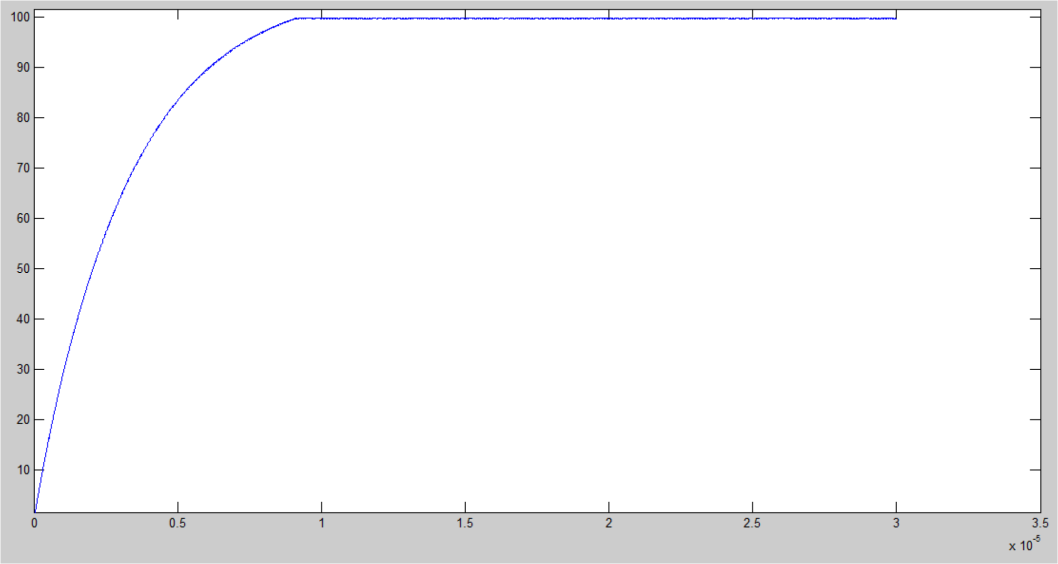
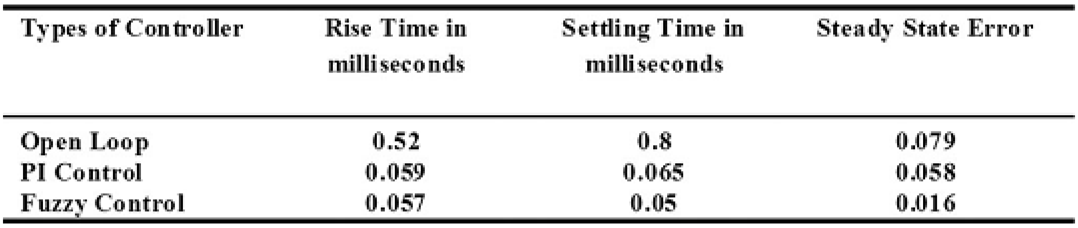


Figure 4.12-c: Simulated output voltage for FLC (Sugeno) system

4.6 Result comparison

Table 4.2: Summary of dynamic response (Experimental results) for LCL resonant converter [15]



Types of Controller	Rise Time in milliseconds	Settling Time in milliseconds	Steady State Error
Open Loop	0.52	0.8	0.079
PI Control	0.059	0.065	0.058
Fuzzy Control	0.057	0.05	0.016

Table 4.3 Illustrates result comparison between FLC (Mamdani) system and FLC (Sugeno) system LCL RC and FLC Closed Loop LCL RC Response in reference [15].

Table 4.3: LCL resonant converter Result comparison

Types of Controller	**Rise Time inmilliseconds**	**Settling Time in milliseconds**	**Steady StateError**
FLC Closed Loop	0.057	0.07	0.016
FLC (Mamdani) system	0.0027	0.005	0.0014
FLC (Sugeno) system	0.0024	0.0046	0.0014

Sample Calculation for 100% Load is given below:

$$\%Efficiency = \frac{Output\ power}{Input\ Power} \qquad (4.4)$$

$$\%Efficiency = \frac{1.33 \times 100}{1.16 \times 125} = \frac{133}{145} = 91.7\%$$

So the Efficiency that using FLC (Sugeno)system for the LCL RC is less than the efficiency using FLC (Mamdani) closed loop response for previous work as 92.86% but the output voltage not very smooth as like the FLC(Sugeno) at this thesis.

CHAPTER 5 CONCLUSION

5.1 CONCLUSION

Issues in the design and implementation of controllers for LCL RC have been discussed in this dissertation. There are many control methods that may be used to design controllers for LCL RC. Generally, these methods fall into two categories: linear and nonlinear control methods. Among the various techniques of artificial intelligence, the most popular and widely used technique in control systems is fuzzy control. Fuzzy controllers were designed based on the general knowledge of the converters. In this thesis, fuzzy logic controller was designed to improve the system response such as settling time, When implementing the fuzzy controller inference system(Mamdani)closed loop in the previous works, the authors got a voltage output of 99.6 of set voltage100v . The setting time was 0.05, the rise time was 0.057 and the steady state error was 0.016. But when we measured the output by using the value of the steady state error we found that the voltage is 98.6 and not 99.6. In this thesis we implement the fuzzy controller inference system (Mamdani) but the input membership function and the output membership function are different. The voltage output was 99.8, the setting time was 0.005, the rise time was 0.0027 and the steady state error was 0.0014. we made another implementation to the Fuzzy inference system by(Sugeno) method and the output voltage was 99.86, the setting time was 0.0046, the rise time was 0.0024 and the steady state error was 0.0014. We got better results than the results of the previous works but however we faced a lot of problems like that there were inaccurate figures in the equation of the electronic circuits. There were errors in the values of the output voltage that when measured again were different. Also there were some values that were copied from other works without any changes but we edited it. After correcting the values they were implemented by using the Matlab/ simulation and got better results . we made a comparison between the results that were shown in a table before . we changed the output voltage to get a better value with no ripple that obstacle the system.

5.2 Future Research

1- In the future research the GA can be used instead of sugenu model and make comparison between two methods.
2- Using fuzzy supervised PID techniques to give better results.
3- We can implement the FLC for (LCLRC) by using the modern technique in FPGA.

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APPENDIX A MATLAB PROGRAMS

Appendix A: The Rule Base Of Mamdani Fuzzy Controller For LCL RC.

1.IF (Error is NB) and (Ch-Error is NB) then (Speed is NB).

2.IF (Error is NM) and (Ch-Error is NB) then (Speed is NB).

3. IF (Error is NS) and (Ch-Error is NB) then (Speed is NB).

4. IF (Error is Z) and (Ch-Error is NB) then (Speed is NB).

5. IF (Error is PS) and (Ch-Error is NB) then (Speed is NM).

6. IF (Error is PM) and (Ch-Error is NB) then (Speed is NS).

7. IF (Error is PM) and (Ch-Error is NB) then (Speed is Z).

8. IF (Error is NB) and (Ch-Error is NM) then (Speed is NB).

9. IF (Error is NM) and (Ch-Error is NM) then (Speed is NB).

10. IF (Error is NS) and (Ch-Error is NM) then (Speed is NM).

11. IF (Error is Z) and (Ch-Error is NM) then (Speed is NM).

12. IF (Error is PS) and (Ch-Error is NM) then (Speed is NS).

13. IF (Error is PM) and (Ch-Error is NM) then (Speed is Z).

14. IF (Error is PM) and (Ch-Error is NM) then (Speed is PS).

15. IF (Error is NB) and (Ch-Error is NS) then (Speed is NB).

16. IF (Error is NM) and (Ch-Error is NS) then (Speed is NM).

17. IF (Error is NS) and (Ch-Error is NS) then (Speed is NS).

18. IF (Error is Z) and (Ch-Error is NS) then (Speed is NS).

19. IF (Error is PS) and (Ch-Error is NS) then (Speed is Z).

20. IF (Error is PM) and (Ch-Error is NS) then (Speed is PS).

21. IF (Error is PB) and (Ch-Error is NS) then (Speed is PM).

22. IF (Error is NB) and (Ch-Error is Z) then (Speed is NB).

23. IF (Error is NM) and (Ch-Error is Z) then (Speed is NM).

24. IF (Error is NS) and (Ch-Error is Z) then (Speed is NS).

25. IF (Error is Z) and (Ch-Error is Z) then (Speed is Z).

26. IF (Error is PS) and (Ch-Error is Z) then (Speed is PS).

27. IF (Error is PM) and (Ch-Error is Z) then (Speed is PM).

28. IF (Error is PB) and (Ch-Error is Z) then (Speed is PB).

29. IF (Error is NB) and (Ch-Error is PS) then (Speed is NM).

30.IF (Error is NM) and (Ch-Error is PS) then (Speed is NS).

31.IF (Error is NS) and (Ch-Error is PS) then (Speed is Z).

32.IF (Error is Z) and (Ch-Error is PS) then (Speed is PS).

33.IF (Error is PS) and (Ch-Error is PS) then (Speed is PS).

34.IF (Error is PM) and (Ch-Error is PS) then (Speed is PM).

35.IF (Error is PB) and (Ch-Error is PS) then (Speed is PB).

36.IF (Error is NB) and (Ch-Error is PM) then (Speed is NS).

37.IF (Error is NM) and (Ch-Error is PM) then (Speed is Z).

38.IF (Error is NS) and (Ch-Error is PM) then (Speed is PS).

39.IF (Error is Z) and (Ch-Error is PM) then (Speed is PM).

40.IF (Error is PS) and (Ch-Error is PM) then (Speed is PM).

41.IF (Error is PM) and (Ch-Error is PM) then (Speed is PB).

42.IF (Error is PB) and (Ch-Error is PM) then (Speed is PB).

43.IF (Error is NB) and (Ch-Error is PB) then (Speed is Z).

44.IF (Error is NM) and (Ch-Error is PB) then (Speed is PS).

45.IF (Error is NS) and (Ch-Error is PB) then (Speed is PM).

46.IF (Error is Z) and (Ch-Error is PB) then (Speed is PB).

47.IF (Error is PS) and (Ch-Error is PB) then (Speed is PB).

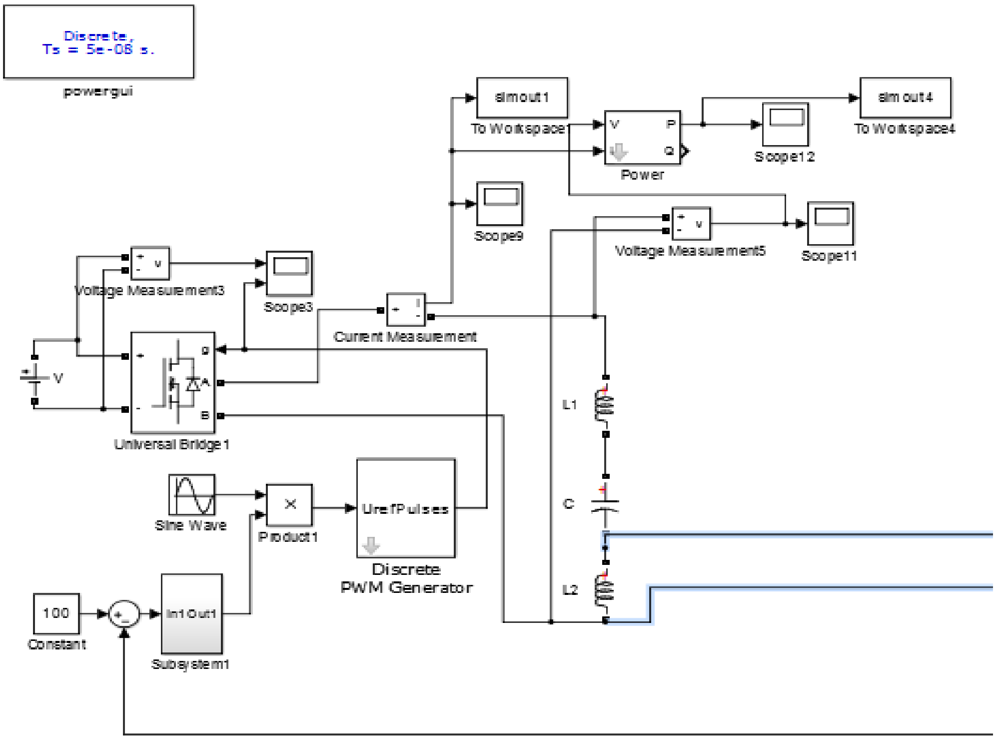
48.IF (Error is PM) and (Ch-Error is PB) then (Speed is PB).

49.IF (Error is PB) and (Ch-Error is PB) then (Speed is PB).

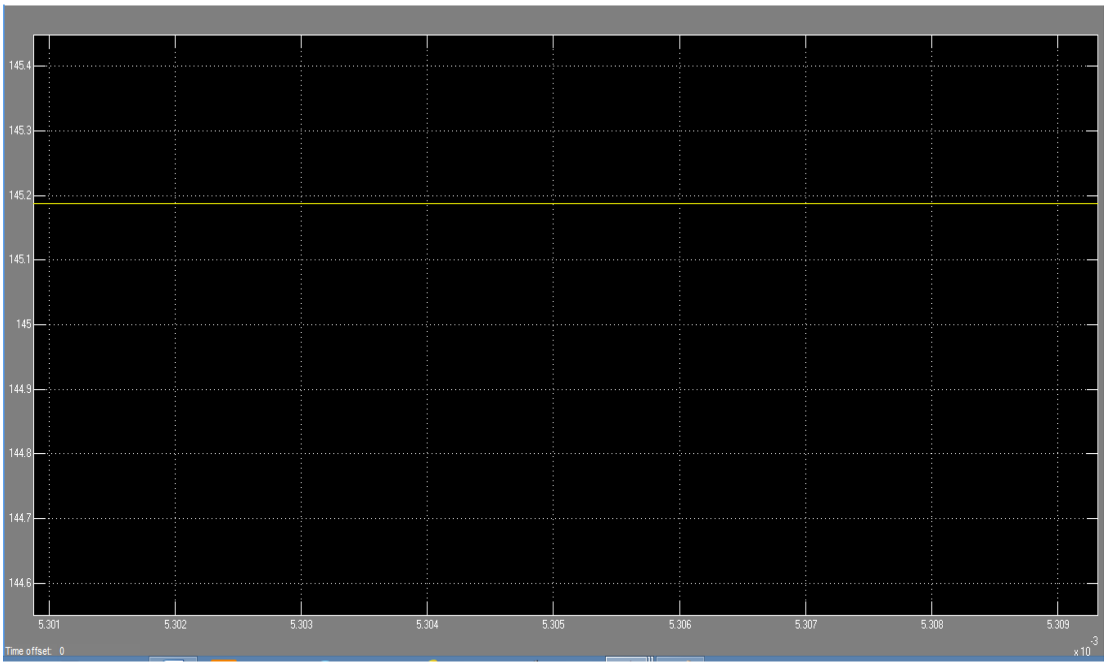
APPENDIX B MATLAB SIMULINK

Appendix B: The Input, Output Power For The LCL RC

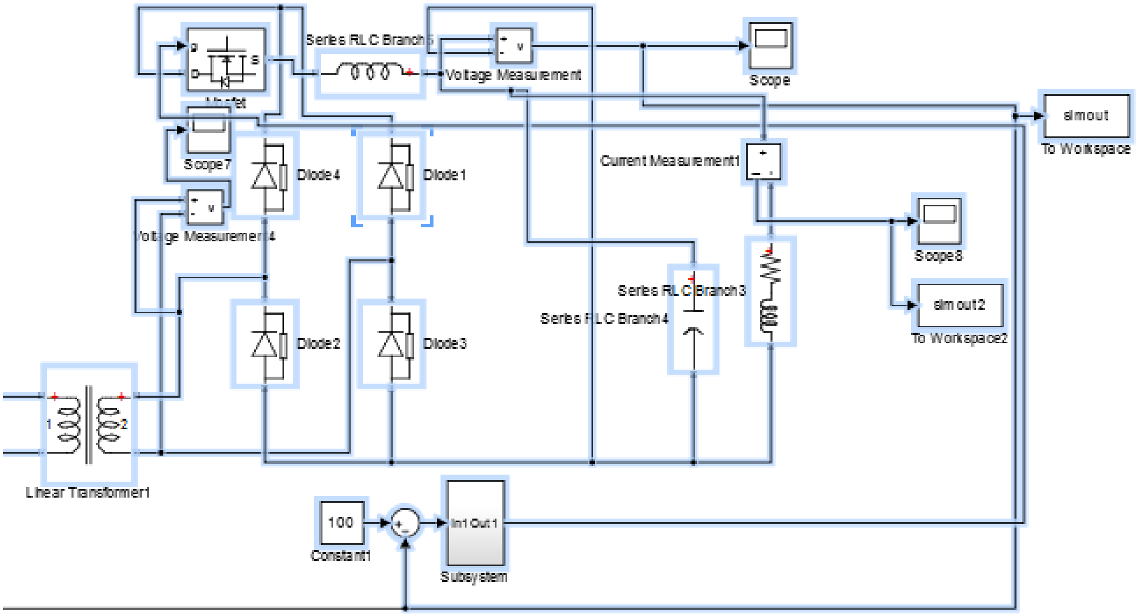
The PWM Generator that used to control the bridge Mosfet



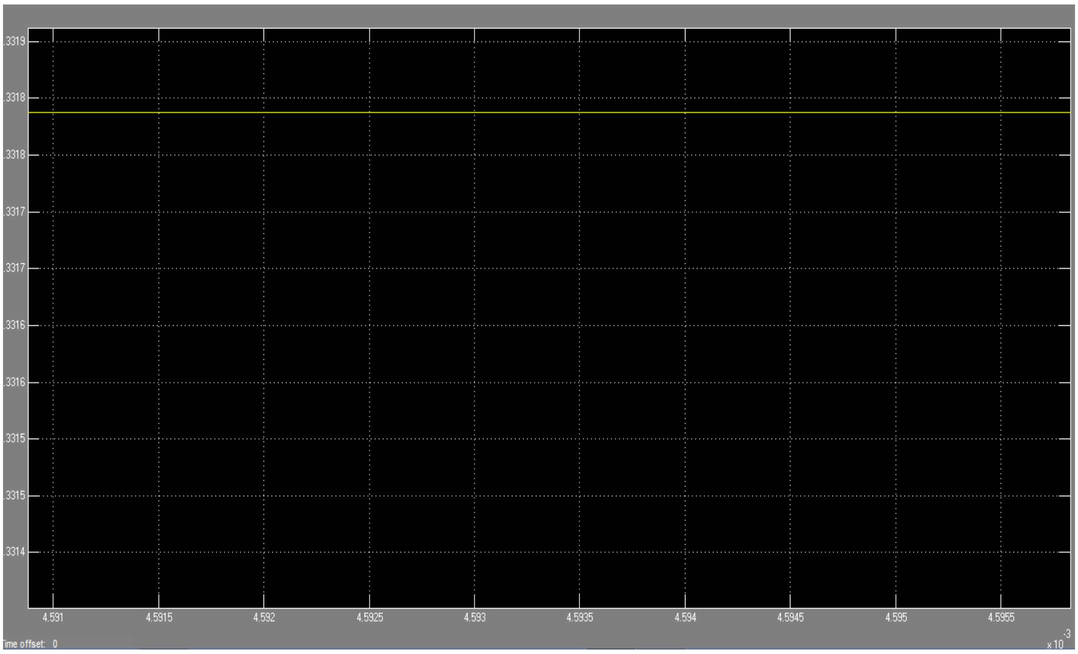
The Input Power For The LCL RC



The Filter Circuit For The LCL RC



The Output Current For The LCL RC



The Output Voltage For The LCL RC