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IMPLEMENTATION OF BRIDGELESS CUK POWER FACTOR CORRECTOR WITH POSITIVE OUTPUT VOLTAGE

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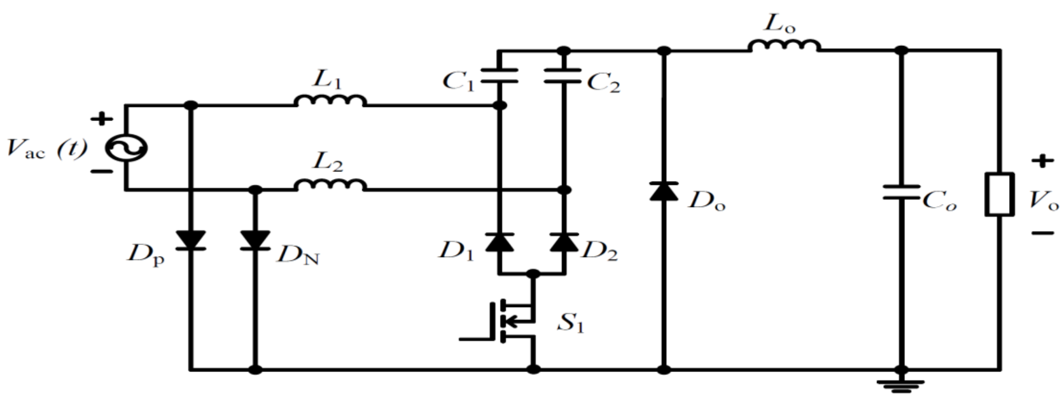
ABSTRACT

A single-phase, bridgeless Cuk AC/DC power factor correction (PFC) rectifier with positive output voltage is proposed in this paper. For low output voltage product applications, the rectifier is designed to convert high input voltage to low output voltage. Due to no bridge-diodes required and thus decreased input conduction losses, the proposed rectifier efficiency can be improved. The proposed rectifier operates in discontinuous conduction mode (DCM) and the current-loop circuit is hence not needed. Also, only a single switch is used in the rectifier to simplify the control circuit design. A simple translation method to have the positive output voltage in the Cuk converter is presented in the rectifier to reduce the component counts and the cost as well. The operational principles, steady-state analysis, and design procedure of the proposed rectifier are addressed in detail in this paper. Simulation and experimental results obtained from a 150 W-rated prototype circuit with input 90 Vrms -130 Vrms, 60 Hz, and output 48 Vdc have verified the validity of the proposed rectifier.

Keywords: AC-DC power converters, voltage control, bridgeless, Cuk, PFC, DCM, positive output voltage, ZCS

INTRODUCTION



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CIRCUIT DESCRIPTION

This circuit is designed to find the power factor in the power line. The power line voltage and current is monitored through the potential and current transformer respectively.

The potential transformer is used to step down the mains supply voltage to low voltage level. The voltage level is from 440V AC to 6V AC. Then the output of the transformer is given to Zero Crossing Detector. The current consumed by the load is measured with the help of a current transformer. The current transformer will convert the load current in to lower values that current output will be converted in to voltage with the help of the shunt resistor. Then the corresponding the AC voltage is given to zero crossing detector. The Zero Crossing Detector is used to convert the sine wave to square wave signal.

The zero crossing detectors are constructed by the operational amplifier LM 741. The inverting and non inverting input terminals are connected to the potential transformer and current transformer terminals respectively. So the input sine wave signal is converted in to square wave signals. The square signal is in the range of +12v to -12v level. Then the square wave signal is given to base of the BC 547 switching transistor in order to convert the TTL voltage 0 to 5v level. Then the both ZCD's outputs are given to logical XOR gate 74LS86 to find the phase angle difference between the voltage and current. The XOR gate output is given to microcontroller or PC and calculated the power factor with help of software.

BLOCK DIAGRAM

Block diagram of implementation of bridge less PFC using cuk converter in discontinuous conduction mode is shown below.

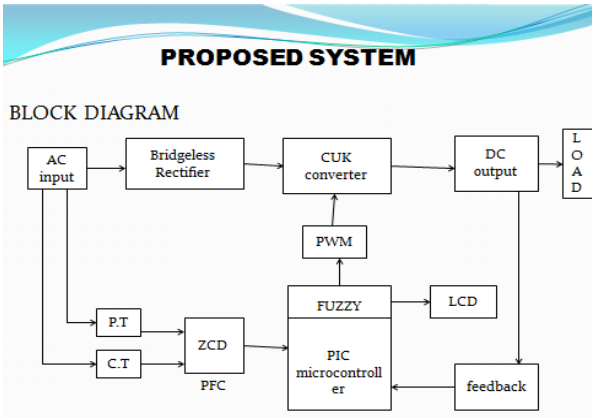


Fig. No. 1 Block Diagram of Proposed System.

FUZZY LOGIC CONTROLLER

Basic principles of fuzzy logic

Fuzzy logic is a complex mathematical method that allows solving difficult simulated problems with many inputs and output variables. Fuzzy logic is able to give results in the form of recommendation for a specific interval of output state, so it is essential that this mathematical method is strictly distinguished from the more familiar logics, such as Boolean algebra. This paper contains a basic overview of the principles of fuzzy logic.

Fuzzy Logic System

Today control systems are usually described by mathematical models that follow the laws of physics, stochastic models or models which have emerged from mathematical logic. A general difficulty of such constructed model is how to move from a given problem to a proper mathematical model. Undoubtedly, today's advanced computer technology makes it possible; however managing such systems is still too complex.

These complex systems can be simplified by employing a tolerance margin for a reasonable amount of imprecision, vagueness and uncertainty during the modelling phase. As an outcome, not completely perfect system comes to existence;

nevertheless in most of the cases it is capable of solving the problem in appropriate way. Even missing input information has already turned out to be satisfactory in knowledge-based systems.

Fuzzy logic allows to lower complexity by allowing the use of imperfect information in sensible way. It can be implemented in hardware, software, or a combination of both. In other words, fuzzy logic approach to problems' control mimics how a person would make decisions, only much faster.

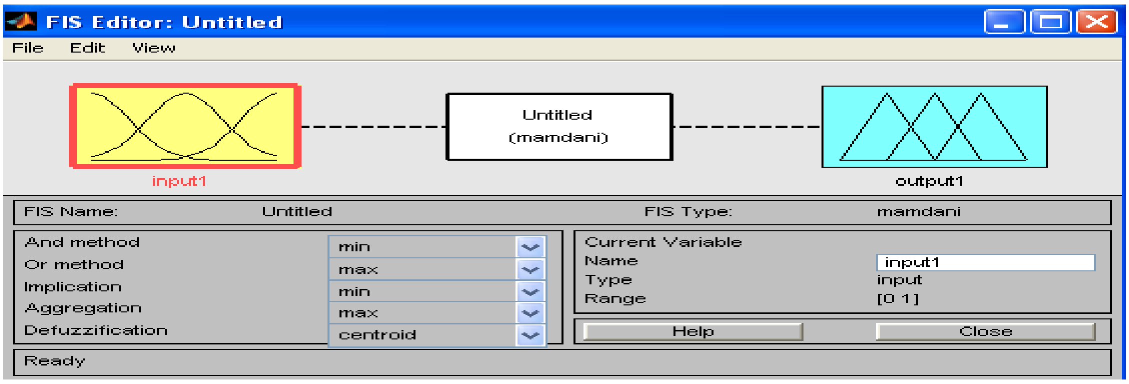


Fig. No 2 Fuzzy logic analysis and control

The fuzzy logic analysis and control methods shown in Figure can be described as:

1. Receiving one or large number of measurements or other assessment of conditions existing in some system that will be analysed or controlled.
2. Processing all received inputs according to human based, fuzzy "if-then" rules, which can be expressed in simple language words, and combined with traditional non-fuzzy processing.
3. Averaging and weighting the results from all the individual rules into one single output decision or signal which decides what to do or tells a controlled system what to do. The result output signal is a precise defuzzified value.

Fuzzy logic control system is created from four major elements presented on Fig: fuzzification interface, fuzzy inference engine, fuzzy rule matrix and defuzzification interface. Each part along with

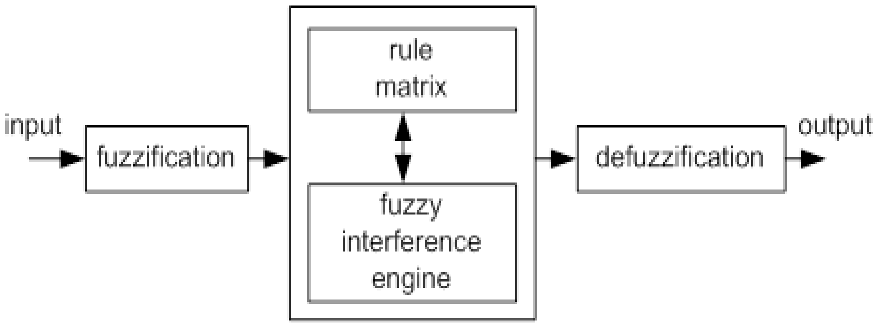


Fig. No 3 Fuzzy logic controller

basic fuzzy logic operations will be described in more detail below.

Fuzzy Logic Basic Operations

Below some basic information about fuzzy logic will be presented, while a comprehensive theory of fuzzy logic can be found in.

- **Universe of Discourse**

It is a range of all possible values considered as fuzzy system input.

- **Fuzzy Set**

A fuzzy set μ is a function from the reference set X to the unit interval, i.e.

$$\mu : X \rightarrow [0,1]$$

$\mu(X)$ represents the set of all fuzzy sets of X.

- **Membership Function**

It is a graphical representation of fuzzy sets, $\mu_F(x)$.

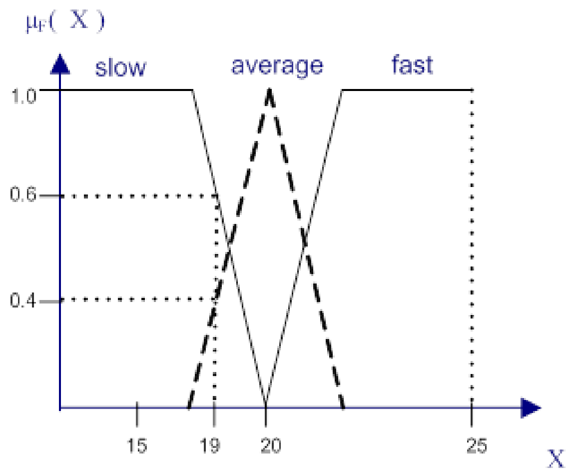


Fig. No 4 An example of fuzzy logic membership function

Above figure shows the membership functions of three fuzzy sets, "slow", "average", and "fast", for a fuzzy variable *Velocity*. The universe of discourse creates all possible values of *Velocity*, i.e., $X = 19$. For *Velocity* value 19 km/h, the fuzzy set "slow" has the membership value 0.6. Hence, $\mu_{slow}(19) = 0.6$. Similarly, $\mu_{average}(19) = 0.4$, and $\mu_{fast}(19) = 0$.

- **Support**

The support of a fuzzy set F is the crisp set of all points in the Universe of Discourse U such that membership function of F does not equal zero

$$\mu_F(u) > 0$$

- **Crossover point**

It is an element in U where its membership function equals 0.5.

- **Centre**

The centre of a fuzzy set F is the point (or points) at which $\mu_F(u)$ achieves its maximum value.

Fuzzification Method

First phase of fuzzy logic proceeding is to deliver input parameters for given fuzzy system based on which the output result will be calculated. These parameters are fuzzified with use of pre-defined input membership functions, which can have different shapes. The most common are: triangular shape, however bell, trapezoidal, sinusoidal and exponential can be also used. Simpler functions will not require complex computing and will not overload the implementation. The degree of membership function is determined by placing a chosen input variable on the horizontal axis, while vertical axis shows quantification of grade of membership of the input variable. The only condition a membership function must meet is that it must vary between zero and one. The value zero means that input variable is not a member of the fuzzy set, while the value one means that input variable is fully a member of the fuzzy set.

With each input parameter there is a unique membership function associated. The membership functions associate a weighting factor with values of each input and the effective rules. These weighting factors determine the degree of influence or degree of membership (DOM) each active rule has. By computing the logical product of the membership weights for each active rule, a set of fuzzy output response magnitudes are produced. All that remains is to combine and defuzzify these output responses.

Rule Matrix

The rule matrix is used to describe fuzzy sets and fuzzy operators in form of conditional statements. A single fuzzy if-then rule can be as follows

If *x* is A then *y* is Z,

where A is a set of conditions that have to be satisfied and Z is a set of consequences that can be inferred.

In rule with multiple parts, fuzzy operators are used to combine more than one input: AND = min, OR = max and NOT = additive complement. Geometrical demonstration of fuzzy operators is shown in Figure 4.

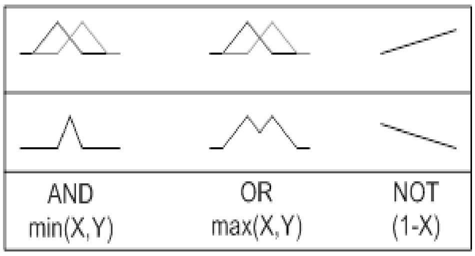


Fig. No 5 Graphical interpretation of fuzzy operators

The rule matrix is a simple graphical tool for mapping the fuzzy logic control system rules. It accommodates two or more input variables and expresses their logical product (AND or OR) as one output response variable. The degree of membership for rule matrix output can take value of maximum, minimum of the degree of previous of the rule [1]. It is often probable, that after evaluation of all the rules applicable to the input, we get more than one value for the degree of membership. In this case, the simulation has to take into consideration, all three possibilities, the minimum, the maximum or an average of the membership-degrees.

Inference Mechanisms

Inference mechanism allows mapping given input to an output using fuzzy logic. It uses all pieces described in previous sections: membership functions, logical operations and if-then rules. The most common types of inference systems are Mamdani and Sugeno. They vary in ways of determining outputs.

Fuzzy Interference System (FIS)

A fuzzy inference system (FIS) is a system that uses fuzzy set theory to map inputs (features in the case of fuzzy classification) to outputs (classes in the case of fuzzy classification). Some of the FIS types are

- Mamdani method

RESULTS AND DISCUSSION AS APPLICABLE (OR) MAMDANI METHOD

An example of a Mamdani inference system is shown in following figure. To compute the output of this FIS given the inputs, one must go through six steps:

1. determining a set of fuzzy rules
2. fuzzifying the inputs using the input membership functions,
3. combining the fuzzified inputs according to the fuzzy rules to establish a rule strength,
4. finding the consequence of the rule by combining the rule strength and the output membership function,
5. combining the consequences to get an output distribution, and

6. defuzzifying the output distribution (this step is only if a crisp output (class) is needed). The following is a more detailed description of this process.

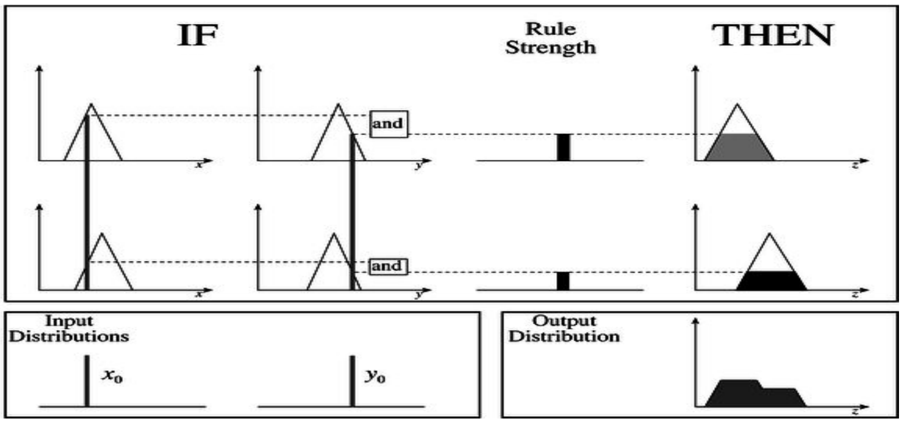


Fig. No 6A two input, two rule Mamdani FIS with crisp inputs

Creating fuzzy rules

Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output. Fuzzy rules are always written in the following form:

if(input1 is membership function1) and/or (input2 is membership function2) and/or. then ($output_n$ is output membership $function_n$).

For example, one could make up a rule that says:

if temperature is high and humidity is high then room is hot.

There would have to be membership functions that define what we mean by high temperature (input1), high humidity (input2) and a hot room (output1). This process of taking an input such as temperature and processing it through a membership function to determine what we mean by "high" temperature is called fuzzification and is discussed in section . Also, we must define what we mean by "and" / "or" in the fuzzy rule. This is called fuzzy combination and is discussed in section.

Fuzzification

The purpose of fuzzification is to map the inputs from a set of sensors (or features of those sensors such as amplitude or spectrum) to values from 0 to 1 using a set of input membership functions. In the example shown in their are two inputs, x_0 and y_0 shown at the lower left corner. These inputs are mapped into fuzzy numbers by drawing a line up from the inputs to the input membership functions above and marking the intersection point.

These input membership functions, as discussed previously, can represent fuzzy concepts such as "large" or "small", "old" or "young", "hot" or "cold", etc. For example, x_0 could be the EMG energy coming from the front of the forearm and y_0 could be the EMG energy coming from the back of the forearm. The membership functions could then represent "large" amounts of tension coming from a muscle or "small" amounts of tension. When choosing the input membership functions, the definition of what we mean by "large" and "small" may be different for each input.

Fuzzy Logic Controller

The dc chopper present in the SMES circuit is switched according to the need that is charging or discharging. The duty cycle is controlled by the fuzzy logic controller taking the active power of the system and current through the coil. The rules as shown in table.1 are created according to the variation in the values of power and current in the system. Fig. shows the duty ratio according to the power and SMES current.

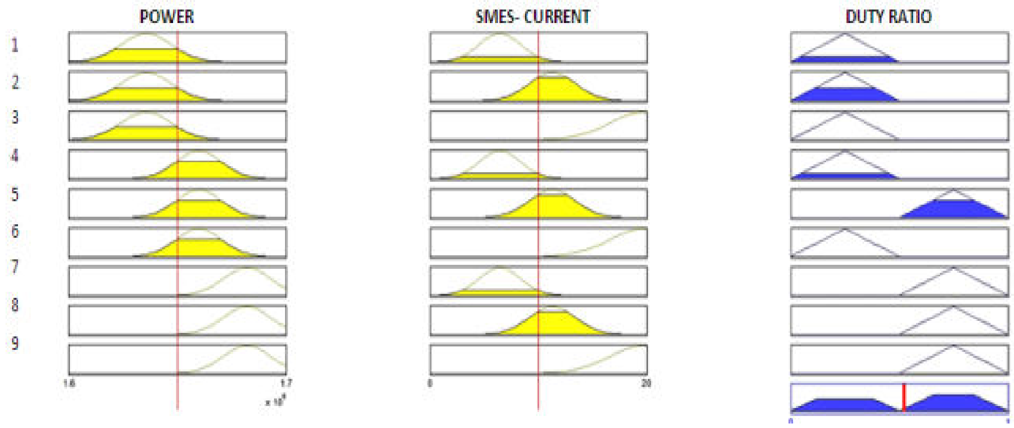


Fig. No 7 Duty ratio for chopper from fuzzy logic controller

CUK CONVERTER

- The Ćuk converter (pronounced Chook, sometimes incorrectly spelled Cuk, Čuk or Cúk) is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.
- The non-isolated Ćuk converter can only have opposite polarity between input and output. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. It is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design.[1]
- Non-isolated Ćuk converter
- There are variations on the basic Cuk converter. For example, the coils may share single magnetic core, which drops the output ripple, and adds efficiency. Because the power transfer flows continuously via the capacitor, this type of switcher has minimized EMI radiation. The Cuk converter enables the energy flow bidirectionally, by adding a diode and a switch.

OPERATING PRINCIPLE

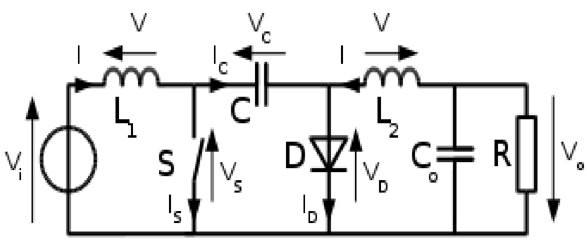


Fig. No 8 Schematic of a non-isolated Ćuk converter.

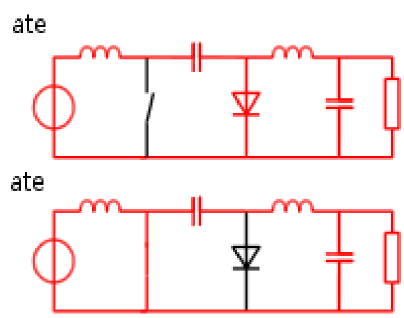


Fig. No 9 The two operating states of a non-isolated Ćuk converter.

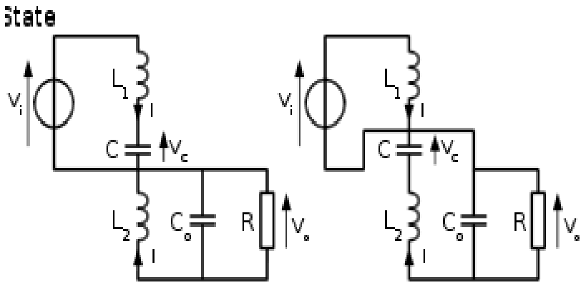


Fig. No 10 The two operating states of a non-isolated Ćuk converter.

In this figure, the diode and the switch are either replaced by a short circuit when they are on or by an open circuit when they are off. It can be seen that when in the Off state, the capacitor C is being charged by the input source through the inductor L1. When in the On state, the capacitor C transfers the energy to the output capacitor through the inductance L2.

A non-isolated Ćuk converter comprises two inductors, two capacitors, a switch (usually a transistor), and a diode. Its schematic can be seen in figure 1. It is an inverting converter, so the output voltage is negative with respect to the input voltage.

The capacitor C is used to transfer energy and is connected alternately to the input and to the output of the converter via the commutation of the transistor and the diode (see figures 2 and 3).

The two inductors L1 and L2 are used to convert respectively the input voltage source (Vi) and the output voltage source (Co) into current sources. Indeed, at a short time scale an inductor can be considered as a current source as it maintains a constant current. This conversion is necessary because if the capacitor were connected directly to the voltage source, the current would be limited only by (parasitic) resistance, resulting in high energy loss. Charging a capacitor with a current source (the inductor) prevents resistive current limiting and its associated energy loss.

As with other converters (buck converter, boost converter, buck-boost converter) the Ćuk converter can either operate in continuous or discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

CONTINUOUS MODE

In steady state, the energy stored in the inductors has to remain the same at the beginning and at the end of a commutation cycle. The energy in an inductor is given by:

$$E = \frac{1}{2}LI^2 \longrightarrow 4.1$$

This implies that the current through the inductors has to be the same at the beginning and the end of the commutation cycle. As the evolution of the current through an inductor is related to the voltage across it:

$$V_L = L\frac{dI}{dt} \longrightarrow 4.2$$

It can be seen that the average value of the inductor voltages over a commutation period have to be zero to satisfy the steady-state requirements. If we consider that the capacitors C and Co are large enough for the voltage ripple across them to be negligible, the inductor voltages become:

- In the off-state, inductor L1 is connected in series with Vi and C (see figure 2). Therefore $V_{L1} = V_i - V_C$. As the diode D is forward biased (we consider zero voltage drop), L2 is directly connected to the output capacitor. Therefore $V_{L2} = V_o$
- In the on-state, inductor L1 is directly connected to the input source. Therefore $V_{L1} = V_i$. Inductor L2 is connected in series with C and the output capacitor, so $V_{L2} = V_o + V_C$

The converter operates in on-state from t=0 to t=D·T (D is the duty cycle), and in off state from D·T to T (that is, during a period equal to (1-D)·T). The average values of VL1 and VL2 are therefore.

$$\bar{V}_{L1} = D \cdot V_i + (1-D) \cdot (V_i - V_C) = (V_i - (1-D) \cdot V_C) \rightarrow 4.3$$

$$\bar{V}_{L2} = D\,(V_o + V_C) + (1-D) \cdot V_o = (V_o + D \cdot V_C) \rightarrow 4.4$$

As both average voltage have to be zero to satisfy the steady-state conditions we can write, using the last equation:

$$V_C = -\frac{V_o}{D} \longrightarrow 4.5$$

So the average voltage across L1 becomes:

$$\bar{V}_{L1} = \left(V_i + (1-D) \cdot \frac{V_o}{D}\right) = 0 \longrightarrow 4.6$$

Which can be written as,

$$\frac{V_o}{V_i} = \frac{-D}{1-D} \longrightarrow 4.7$$

It can be seen that this relation is the same as that obtained for the Buck-boost converter.

DISCONTINUOUS MODE

Like all DC-DC converters Cuk converters rely on the ability of the inductors in the circuit to provide continuous current, in much the same way a capacitor in a rectifier filter provides continuous voltage. If this inductor is too small or below the "critical inductance", then the current will be discontinuous. This state of operation is usually not studied in much depth, as it is not used beyond a demonstrating of why the minimum inductance is crucial.

The minimum inductance is given by:

$$L_1 min = \frac{(1-D)^2 R}{2D f_s} \quad \longrightarrow \quad 4.8$$

Where f_s is the switching frequency.

POWER FACTOR

The power factor of an AC electric power system is defined as the ratio of the real power to the apparent power, and is a number between 0 and 1 (frequently expressed as a percentage, e.g. .5 pf = 50% pf). Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power can be greater than the real power. Low-power-factor loads increase losses in a power distribution system and result in increased energy costs.

Instantaneous and average power calculated from AC voltage and current with a unity power factor (φ=0, cosφ=1)

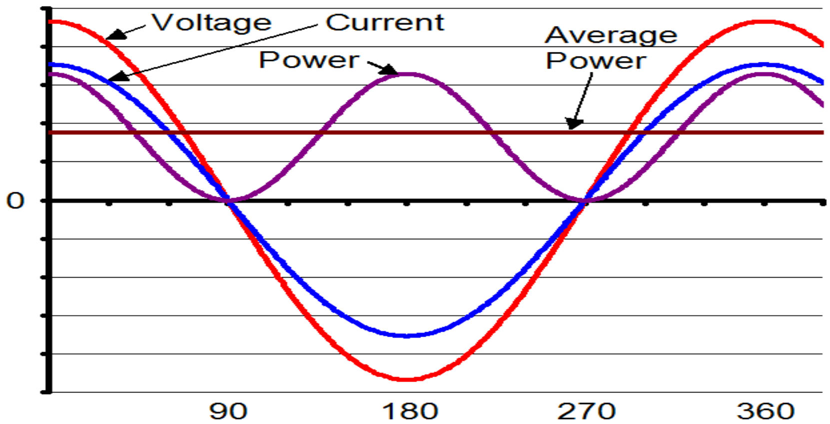


Fig. No 11 Instantaneous and average power with unity power factor.

Instantaneous and average power calculated from AC voltage and current with a zero power factor (φ=90, cosφ=0)

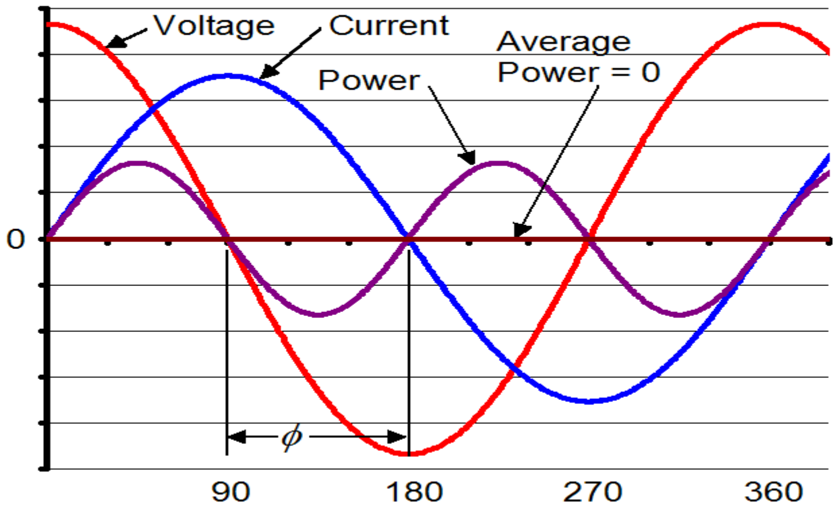


Fig. No 12 Instantaneous and average power with zero power factor.

AC power flow has the three components: real power (P), measured in watts (W); apparent power (S), measured in volt-amperes (VA); and reactive power (Q), measured in reactive volt-amperes (VAr).

The power factor is defined as:

In the case of a perfectly sinusoidal waveform, P, Q and S can be expressed as vectors that form a vector triangle such that:

If is the phase angle between the current and voltage, then the power factor is equal to , and:

Since the units are consistent, the power factor is by definition a dimensionless number between 0 and 1. When power factor is equal to 0, the energy flow is entirely reactive, and stored energy in the load returns to the source on each cycle. When the power factor is 1, all the energy supplied by the source is consumed by the load. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle, where leading indicates a negative sign.

If a purely resistive load is connected to a power supply, current and voltage will change polarity in step, the power factor will be unity (1), and the electrical energy flows in a single direction across the network in each cycle. Inductive loads such as transformers and motors (any type of wound coil) consumes reactive power with current waveform lagging the voltage. Capacitive loads such as capacitor banks or buried cable generate reactive power with current phase leading the voltage. Both types of loads will absorb energy during part of the AC cycle, which is stored in the device's magnetic or electric field, only to return this energy back to the source during the rest of the cycle.

For example, to get 1 kW of real power if the power factor is unity, 1 kVA of apparent power needs to be transferred (1 kW ÷ 1 = 1 kVA). At low values of power factor, more apparent power needs to be transferred to get the same real power. To get 1 kW of real power at 0.2 power factor 5 kVA of apparent power needs to be transferred (1 kW ÷ 0.2 = 5 kVA).

It is often possible to adjust the power factor of a system to very near unity. This practice is known as power factor correction and is achieved by switching in or out banks of inductors or capacitors. For example the inductive effect of motor loads may be offset by locally connected capacitors.

The power factor of an AC electric power system is defined as the ratio of the real power to the apparent power, and is a number between 0 to 1 inclusive. Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power will be equal to or greater than the real power. Low power factor loads increase losses in a power distribution system and results in increased cost for electrical energy use.

In a purely resistive AC circuit, voltage and current waveforms are in step, changing polarity at the same instant in each cycle. Where reactive loads are present, such as with capacitors or inductors, energy storage in the loads result in a time difference between the current and voltage waveforms. This stored energy returns to the source and is not available to do work at the load. A circuit with a low power factor will have thus higher currents to transfer at a given quantity of power than a circuit with a high power factor.

Circuits containing only heating elements (filament lamps, strip heaters, cooking stoves, etc.) have a power factor of 1.0. Circuits containing inductive or capacitive elements (lamp ballasts, motors, etc.) often have a power factor below 1.0. For example, in electric lighting circuits, normal power factor ballasts (NPF) typically have a value of (0.4) - (0.6). Ballasts with a power factor greater than (0.9) are considered high power factor ballasts (HPF).

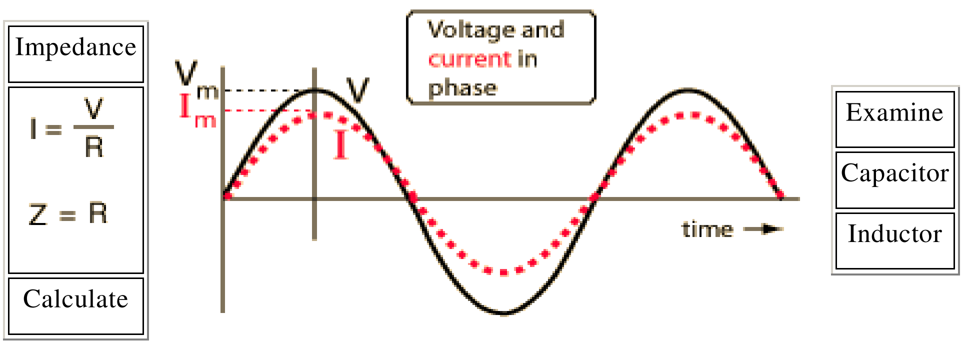
The significance of power factor lies in the fact that utility companies supply customers with volt-amperes, but bill them for watts. Power factors below 1.0 require a utility to generate more than the minimum volt-amperes necessary to supply the real power (watts). This increases generation and transmission costs. Good power factor is considered to be greater than 0.85 or 85%. Utilities may charge additional costs to customers who have a power factor below some limit.

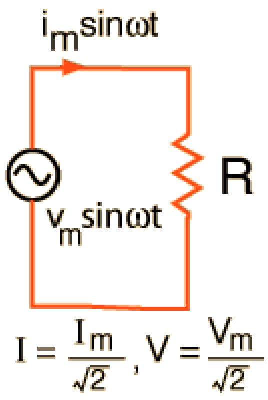
IMPORTANCE OF POWER FACTOR

A power factor of one or "unity power factor" is the goal of any electric utility company since if the power factor is less than one, they have to supply more current to the user for a given amount of power use. In so doing, they incur more line losses. They also must have larger capacity equipment in place than would be otherwise necessary. As a result, an industrial facility will be charged a penalty if its power factor is much different from 1.

Industrial facilities tend to have a "lagging power factor", where the current lags the voltage (like an inductor). This is primarily the result of having a lot of electric induction motors - the windings of motors act as inductors as seen by the power supply. Capacitors have the opposite effect and can compensate for the inductive motor windings. Some industrial sites will have large banks of capacitors strictly for the purpose of correcting the power factor back toward one to save on utility company charges.

RESISTOR AC RESPONSE





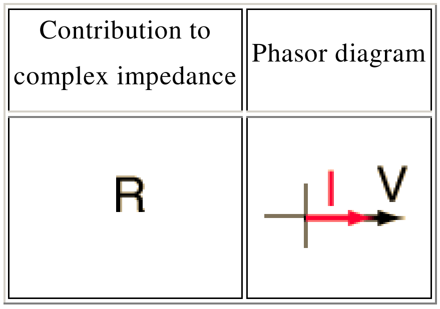
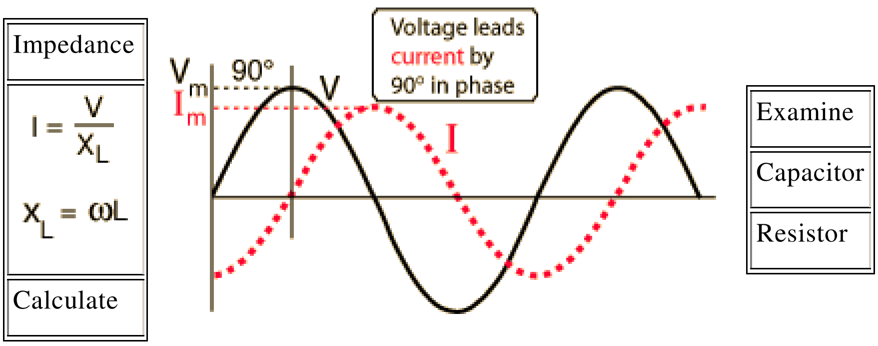
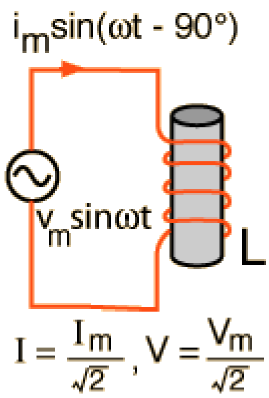


Fig. No 13 Resistor AC responce

For ordinary currents and frequencies the behavior of a resistor is that of a dissipative element which converts electrical energy into heat. It is independent of the direction of current flow and independent of the frequency. So we say that the AC impedance of a resistor is the same as its DC resistance. That assumes, however, that you are using the rms or effective values for the current and voltage in the AC case.

INDUCTOR AC RESPONSE





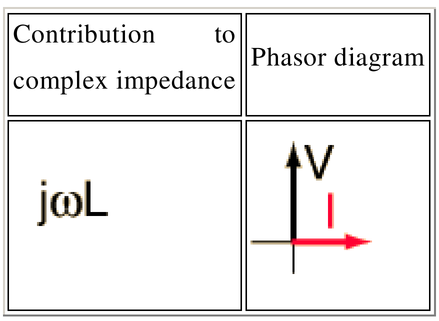


Fig. No 14 Inductor AC response.

The voltage across an inductor leads the current because the Lenz' law behavior resists the buildup of the current, and it takes a finite time for an imposed voltage to force the buildup of current to its maximum.

CAPACITOR AC RESPONSE

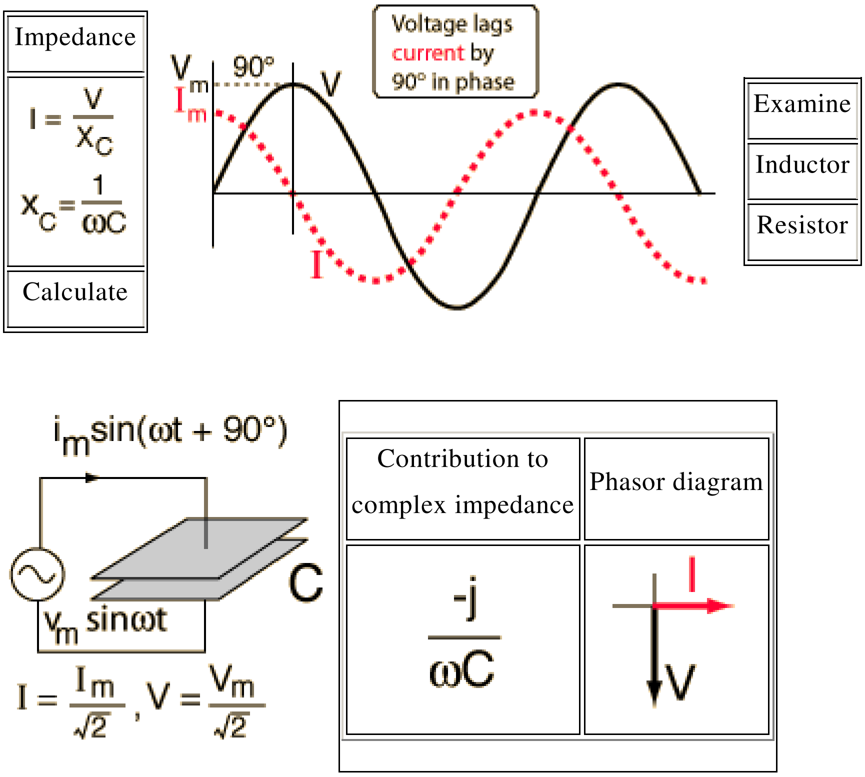


Fig. No 15 Capacitor AC response.

The voltage across a capacitor lags the current because the current must flow to build up the charge, and the voltage is proportional to that charge which is built up on the capacitor plates.

SIMULATION DIAGRAM

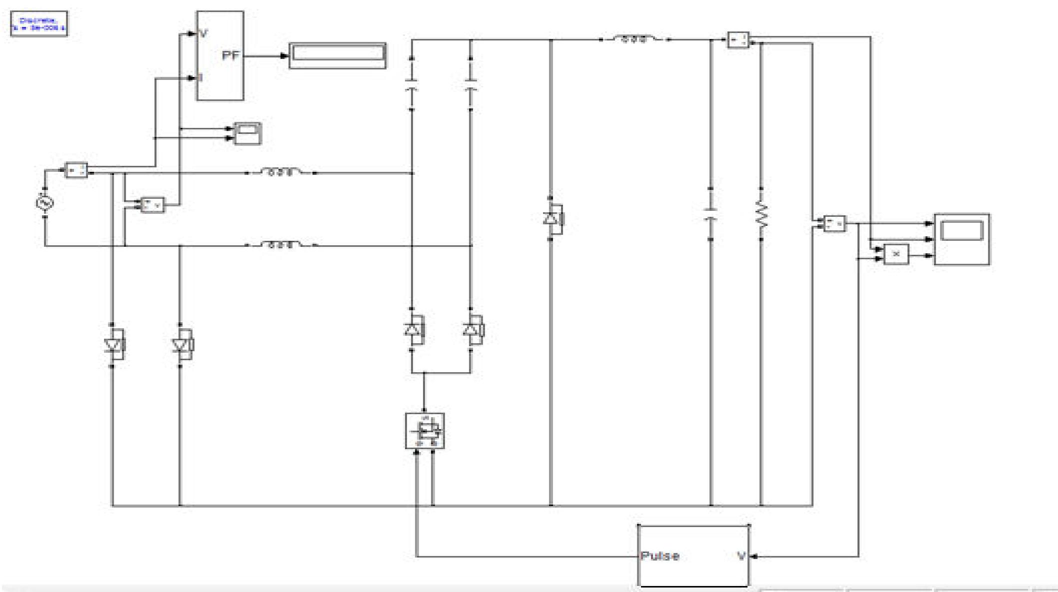


Fig. No 16 Simulation diagram of proposed system.

SIMULATION OUTPUT

FUZZY CONTROLLER

In fuzzy controller,from the output of the cuk converter the feedback signal is taken and giving to the controller. After the fuzzy controller operation the generating pulses are then compared with PWM signals and the pulses are given to cuk converter.

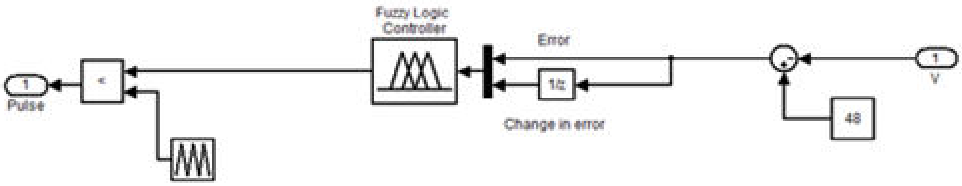


Fig. No 17 Interior diagram of fuzzy controller.

FUZZY CONTROLLER INITIALIZATION

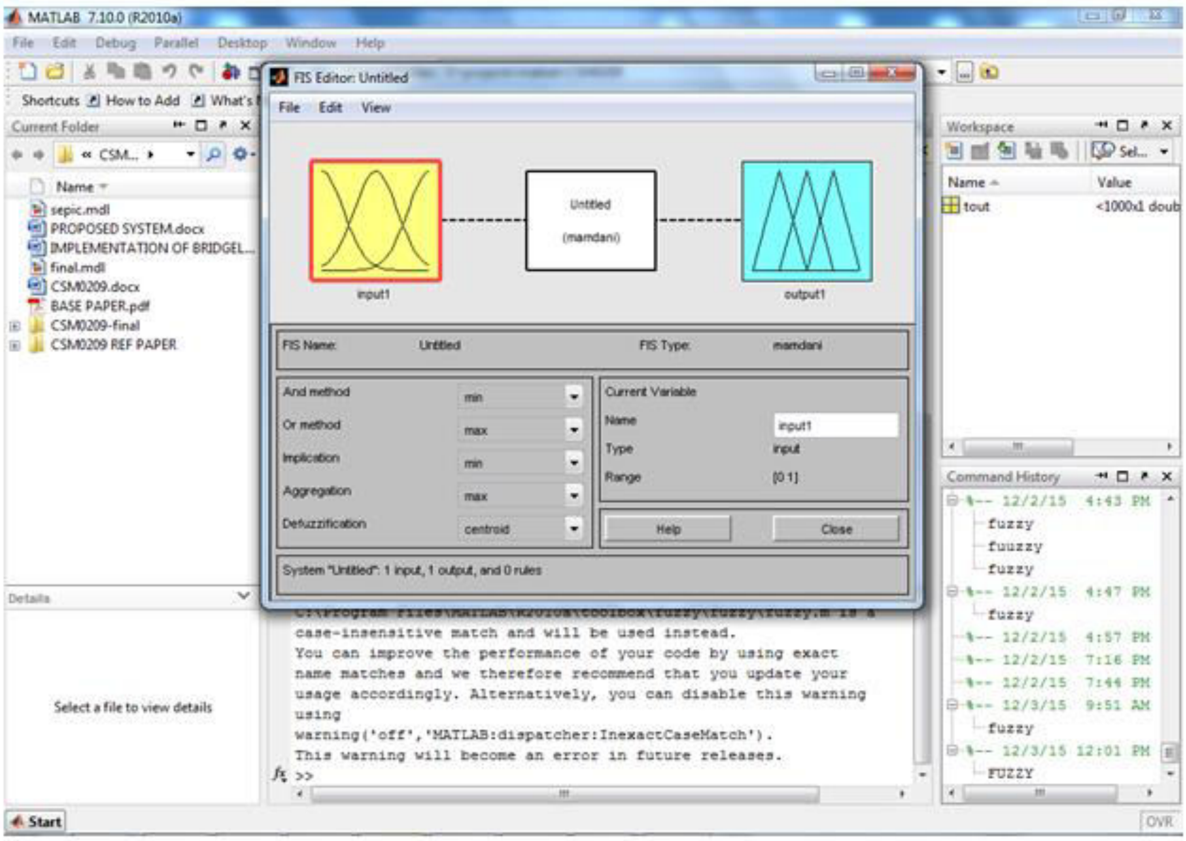
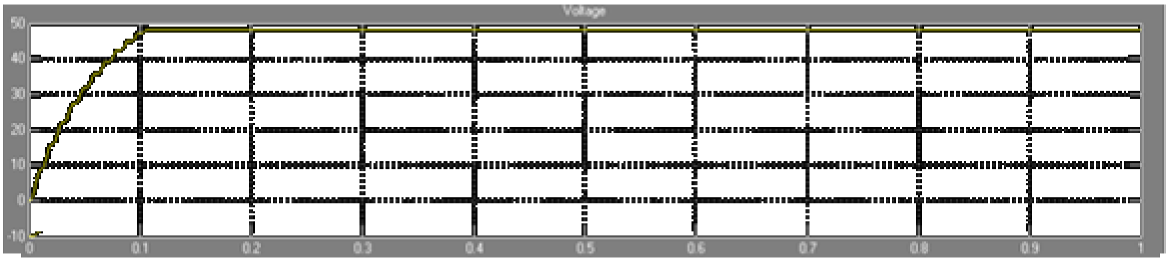


Fig. No 18 Initialization of fuzzy controller.

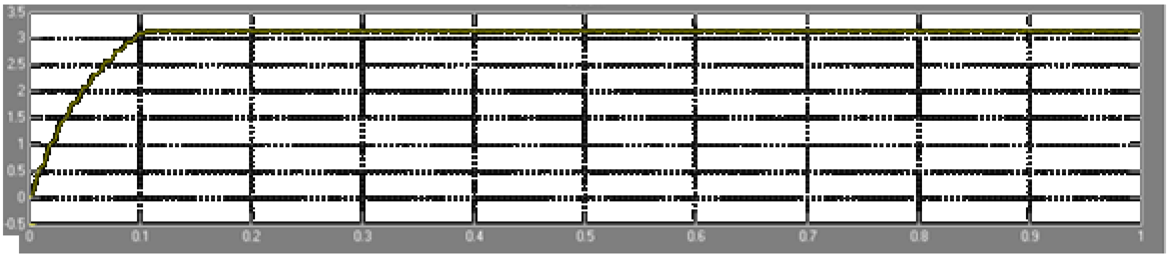
OUTPUT WAVEFORMS

OUTPUT VOLTEGE WAVEFORM



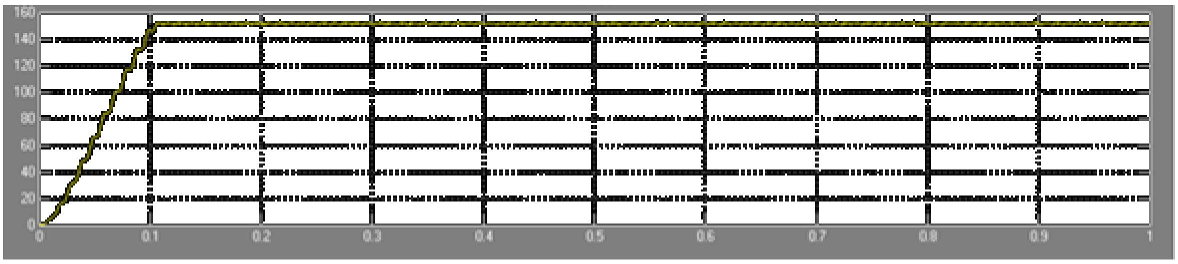
Time →

OUTPUT CURRENT WAVEFORM



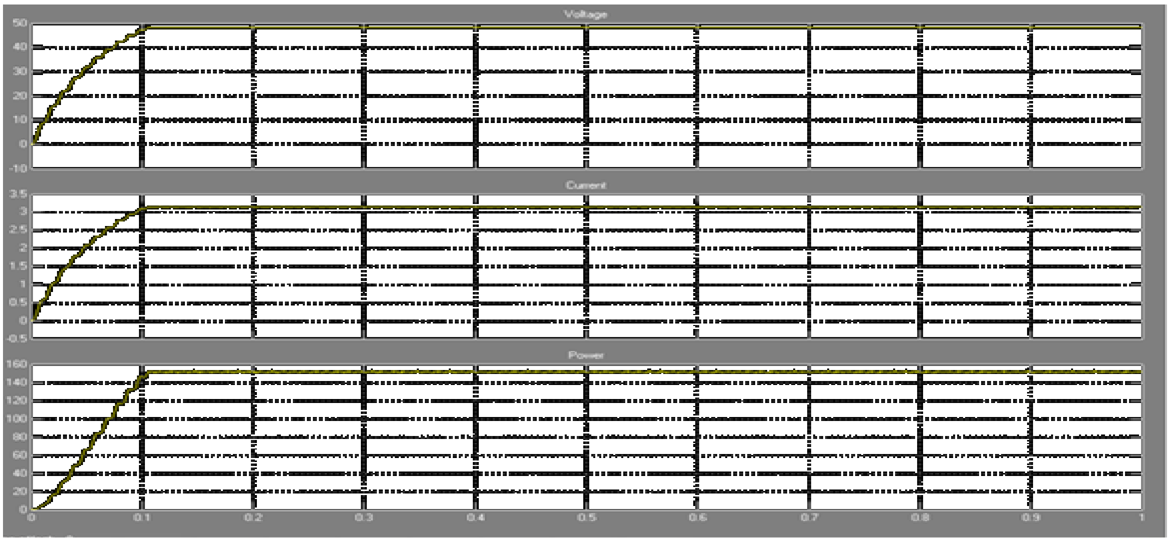
Time →

OUTPUT POWER WAVEFORM

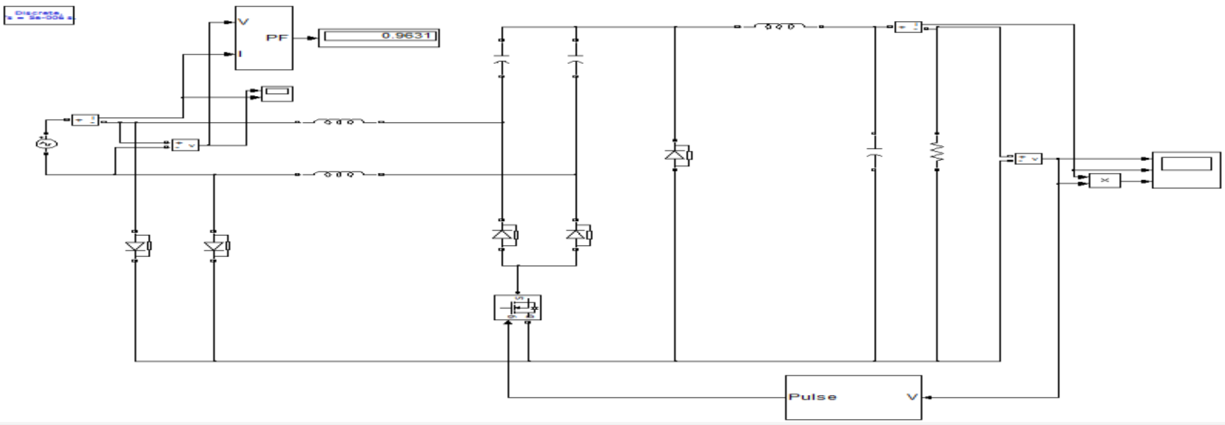


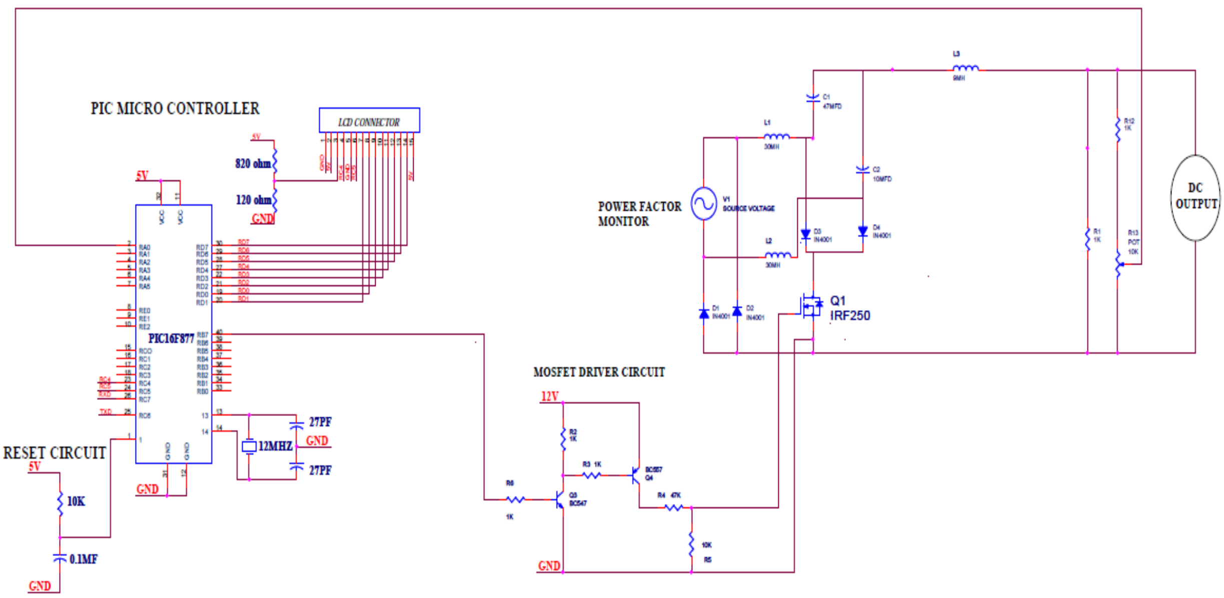
Time →

OUTPUT VOLTAGE, CURRENT AND POWER WAVEFORMS



Time ⟶





REFERENCES

[1] ON Semiconductor®, *Power Factor Correction (PFC) Handbook*, Rev. 4, Feb. 2011.

[2] M. Mahdavi and H. Farzanehfard, "Bridgeless SEPIC PFC Rectifier with Reduced Components and Conduction Losses," *IEEE Transactions Industrial Electronics*, vol. 58, No. 9, pp. 4153-4160, Sep. 2011.

[3] L. Huber, L. Gang, and M. M. Jovanovic, "Design-Oriented Analysis and Performance Evaluation of Buck PFC Front End," *IEEE Transactions Power Electron,* vol. 25, No. 1, Jan. 2010.

[4] Y. Jang and M. M. Jovanovic, "Bridgeless High-Power-Factor Buck Converter," *IEEE Transactions Power Electron,* vol. 26, No. 2, Feb. 2011.

[5] R. Itoh, K. Ishizaka, and H. Okada, "Single-phase buck rectifier employing voltage reversal circuit for sinusoidal input current waveshaping," *IEE Proceedings Electric Power Applications*, vol. 146, No. 6, pp. 707-712, Nov. 1999.

[6] R. Oruganti and M. Palaniapan, "Inductor Voltage Control of Buck-Type Single-Phase AC-DC Converter," *IEEE Transactions Power Electronics*, vol. 15, No. 2, pp. 411-416, Mar. 2010.

[7] M. A. Al-Saffar, E. H. Ismail, and A. J. Sabzali, "Integrated Buck–Boost–Quadratic Buck PFC Rectifier for Universal Input Applications," *IEEE Transactions Power Electronics*, vol. 24, No. 12, pp. 2886-2896, Dec. 2009.

[8] L. Petersen, "Input-Current-Shaper Based on a Modified SEPIC Converter with Low Voltage Stress," in *IEEE 32nd Power Electronics Specialists Conference*, vol. 2, pp. 666-671, Jun. 2001.

[9] P. Scalia, "A Double-Switch Single-Stage PFC Offline Switcher Operating in CCM with High Efficiency and Low Cost," in *IEEE 29th Power Electronics Specialists Conference*, vol. 2, pp. 1041-1047, May 1998.

[10] C. Jingquan, D. Maksimovic, and R. Erickson, "A New Low-Stress Buck-Boost Converter for Universal-Input PFC Applications," in *IEEE 6th Applied Power Electronics Conference*, vol. 1, pp. 343-349, Mar. 2001.

[11] W. Huai and I. Batarseh, "Comparison of Basic Converter Topologies for Power Factor Correction," *in IEEE Proceedings Southeastcon '98*, pp. 348-353, Apr. 1998.

[12] P. F. de Melo, R. Gules, E. F. R. Romaneli, and R. C. Annunziato, "A Modified SEPIC Converter for High-Power-Factor Rectifier and Universal Input Voltage Applications," *IEEE Transaction Power Electronics*, vol. 25, No. 2, pp. 310-321, Feb. 2010.

[13] T. Ching-Jung and C. Chern-Lin, "A Novel ZVT PWM Cuk Power-Factor Corrector," *IEEE Transactions Industrial Electronics*, vol. 46, No. 4, pp. 780-787, Aug. 1999.

[14] D. S. L. Simonetti, J. Sebastian, and J. Uceda, "The Discontinuous Conduction Mode Sepic and Cuk Power Factor Preregulators: Analysis and Design," *IEEE Transactions Industrial Electronics*, vol. 44, No. 5, pp. 630-637, Oct. 1997.

[15] M. Mahdavi and H. Faarzanehfard, "Bridgeless CUK power factor correction rectifier with reduced conduction losses," *IET Power Electron*, vol. 5, lss. 9, pp. 1733-1740, Sep. 2012.