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Design of Power Factor Correction CUK Converter for Electric Vehicle Battery Charging Application

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Abstract*— For charging the batteries of Electric Vehicles (EV), a single-phase, redesigned, non-inverted Cuk converter with power factor adjustment is suggested in this work. In order to charge the battery, the high input ac voltage is converted to a low output dc voltage using a combination of voltage rectification and dc-dc conversion. The suggested converter operates in the discontinuous conduction mode (DCM), and only one power electronic switch is needed, making the control circuit's design straightforward. For EV operation with a battery as the source, a multi-port Single-Input Multiple-Output (SIMO) DC-DC converter is added. The suggested topology can run several loads without experiencing any disruptions. An improved fuzzy logic control technique for the modified CUK converter is suggested to increase the stability of the DC bus voltage. The simulation is to be carried out in MATLAB/Simulink software.

***Index Terms*— Power factor correction, cuk converter, fuzzy logic controller, Electric Vehicle applications, Battery charging**

I. INTRODUCTION

Technologies for switched-mode power supplies have advanced quickly in recent years. The majority of switched mode power supply for electronic equipment convert AC to DC sources for usage in various applications. A bridge rectifier, a transformer, and capacitors may be used to readily create an DC output voltage, however the source current is severely distorted. The PFC conversions are hence crucial for AC-DC conversion. For PFC applications, several circuit architectures have been devised. Because of its ease of use, the converter is commonly utilised.

Because of the converter's boosting behaviour [1], the load voltage continues to be higher than the input voltage. In many applications that make use of low-voltage and low-power supplies, it is preferable to have an output voltage that is lower than the peak of the input voltage. A buck-type conversion is therefore required. The buck converter is hardly ever used in the PFC application. The buck converter would lose control if the line supply voltage was below the output voltage because its input current is discontinuous. Additionally, a second passive techniques filter must be employed at a buck conversion input to filter the incoming current.

A buck PFC rectifier for voltage step-down operations has recently been proposed. However, the supply line current is unable to follow the source voltage when it approaches the source voltage zero crossing [3]. The total harmonic distortion (THD) and power factor both drop as a result of the buck PFC converter. Converters like buck boost, single-ended primary-inductor converters (SEPIC), or Cuk converter are typically used next to a full-bridge rectifier in such situations to obtain a PFC converter with low output voltage. The converters can all be used in continuous conduction (CCM) or direct current mode (DCM). Since these converters have built-in PFC capabilities at fixed duty ratios, no control circuit is needed while they are operating in DCM to provide sinusoidal input current.

Buck-boost converters working in DCM have the disadvantages of excessive stress on semiconductors and interrupted input current, which raises THD. As a result, SEPIC and Cuk converter are other options since they operate in DCM with continuous input currents and output voltages that are below the input voltage. The SEPIC converter, like the boost converter, has the drawback of interrupted output current, leading to a disproportionately high output ripple. Numerous applications, such as standby power supply, LED drivers, & communication networks call for multi-output DC-DC converters.

In order to achieve simple circuits and simplify the design, the flyback converter can provide several outputs with multiple windings. The output voltages cannot, however, be adjusted individually because to the strong cross-regulation, which lowers their total efficiency. SIMO converter has been designed to achieve improved efficiency, yet even with these converters; the cross-regulation issue persists. A crucial factor in guaranteeing the reliability of the DC power grid involves sustaining the integrity of the DC bus voltage. The CPL, on the other hand, exhibits negative impedance features, which lowers the system's damping coefficient and causes the DC bus voltage to fluctuate.

Additionally, the DC micro grid using CPL is a conventional switching nonlinear system, which severely restricts the use of linear control techniques in the development of such system controllers. Fuzzy logic controls are quickly replacing traditional controllers as a practical option. This is because a fuzzy system can accurately mimic human control procedures. When creating an embedded system, fuzzy logic technology permits the application of

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technical expertise and experimental findings. This gets around the need for careful mathematical modelling to arrive at a control solution in many instances. Utilising a fuzzy logic controller technique has the additional benefit of enabling model-free system estimation.

In this case, the designer is not required to specify the mathematical. relationship between the inputs and outputs. The structured system information may be encoded to create a fuzzy controller. This makes it possible to design speedier control algorithms in less time and for less money. Fuzzy logic controllers are a more alluring option for real-time control scenarios as microprocessor and Digital Signal Processing (DSP) technology advances.

This method suggests a bridgeless CUK conversion for charging batteries in EV applications. Cuk converters offer an inverted output, which the control circuit finds undesirable. We reverse the polarity of every component to produce the suggested bridge-less Cuk PFC rectifier, which produces a positive output voltage eliminating need for an inverting amplifier circuit. In comparison to the traditional feedback control circuit, the feedback-controlled circuit is therefore simpler, and the cost may be decreased. This study suggests a novel SIDO DC-DC converter architecture for supplemental power module applications that will power the EV. The proposed converter has the following advantages: (i) it can control two loads independently or simultaneously while producing different output voltages; (ii) minimal duty ratio restrictions (D1 > D2 or D2 D1 or D1 = D2), or port voltage restrictions (V01 > V02 or V01 V02) during control; and (iii) it avoids cross-regulation issues. The creation of a fuzzy logic-based control method used in voltage mode regulation is discussed in this study. In developing the controller, the defuzzification technique, inference, and fuzzy logic theory are covered.

The main purpose of this work is to design a converter system with fewer switches and to apply the power factor correction approach utilizing both the PI and Fuzzy Logic controller methods and its Comparison.

One of the most significant aspects of this work is obtaining an effective power conversion system. Another key feature of this work is the use of SIDO converters to acquire numerous different voltage levels for the application of different loads, hence stopping cross voltage regulation.

II. SYSTEM DESCRIPTION

The. Block diagram of the proposed system is shown below in Fig 1

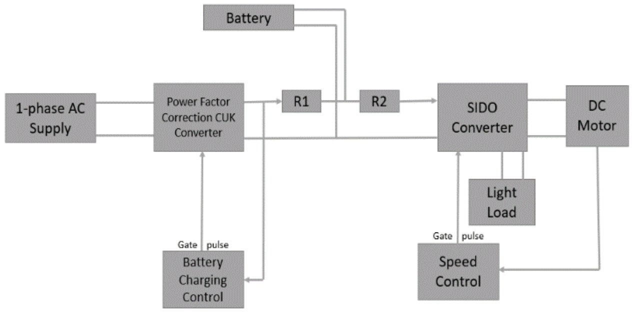

Fig 1: Proposed system Block diagram

In this, the ac supply is converted to dc by PFC cuk converter in order to charge the battery while the vehicle is parked in charging station [2]. During this time i.e. when the vehicle is in parking state (Battery is charging)

R1- Relay1 is ON

R2- Relay2 is OFF

When the vehicle starts to run, the battery starts to discharge, and SIDO converter starts to operate. During this time i.e when the vehicle is in running state (Battery is discharging)

R1- Relay1 is OFF

R2- Relay2 is ON

Other EV loads like Lights, Music system, etc.

PI, Fuzzy Logic Mode control is used for battery charging control and speed control and comparison is made in terms of settling time, peak overshoots, steady state error, voltage and current ripples, efficiency, power factor, %THD, etc.

Bridgeless PFC CUK Converter:

The proposed cuk converter utilised for battery charging is provided below in Fig 2

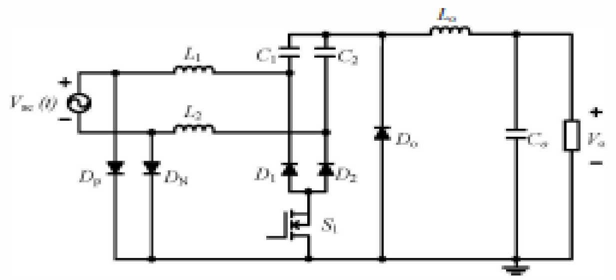

Fig 2: Modified cuk converter

The assumptions made for analyzing the proposed converter in steady state conditions are provided below:

1. The cut in voltage of diodes along with ON state resistance and parasitic capacitance of both MOSFET and diodes are neglected.

2. The input side and output side capacitance value are high enough so that for one complete switching cycle (Ts) capacitor voltages are taken as constant.

3. The DCM mode is followed by the proposed converter.

4. Only positive half cycle operation is analyzed as the proposed converter is symmetrical in both half cycles.

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The operational modes of the proposed converter are provided below:

Mode I: In this, the switch S1 is turned ON.

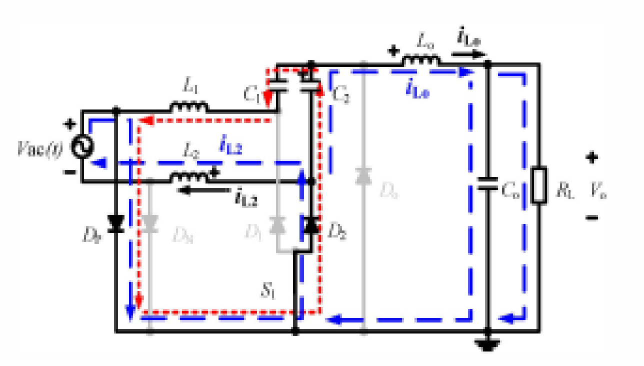

Fig 3: Mode 1 equivalent circuit of modified cuk converter

The Lz getting charged and Dp is conducting. The inductor current will increase and the inductor voltage is same as input voltage [4], Vae(t).

Mode II: In this, the switch S1 is turned OFF and diode Do starts conducting and the inductor Lz starts to discharge and Dp is conducting. The inductor current going to decrease and the inductor voltage will be same as load voltage, Vo.

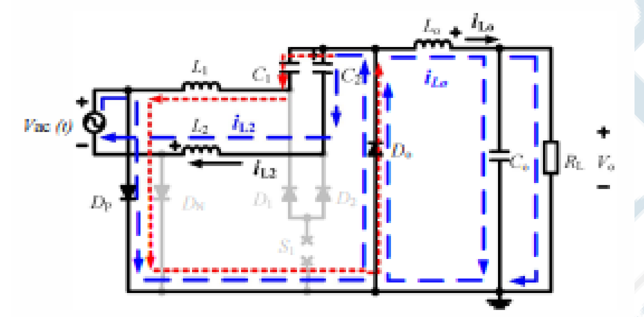

Fig 4: Mode 2 equivalent circuit of modified cuk converter

Mode III: In this, only Dp conducts to provide freewheeling path for inductor current iL2. The inductors L2 and Lo acts as constant current source, and both the inductor voltages (L2 and Lo) are zero. The Capacitor Cz is getting charged by iLl and Co starts discharging and provides supply to load.

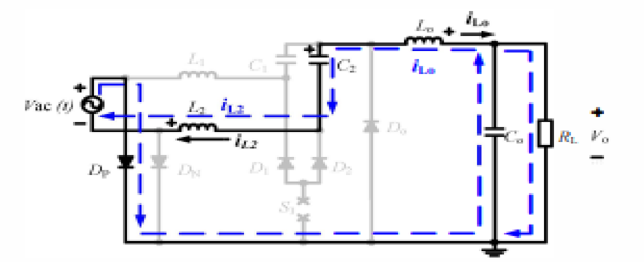

Fig 5: Mode 3 equivalent circuit of modified cuk converter

The inductor (LI and Lz) values are calculated using the following relations given below:

$$L_0 = \frac{V_{IN}*D}{2*\Delta I_L*f}\text{---(1)}$$

The C1 and Cz values are determined based on the values of LJ, Lz and Lo and the line frequency (fL) is to be less than that of switching frequency (Is). The capacitor value is calculated by the relation shown below:

$$f_r = \frac{1}{2\pi\sqrt{C_1(L_1+L_0)}}\text{----------------------------(2)}$$

The output capacitance, Co can be obtained as follows:

$$C_0 = \frac{P_0}{4*f*V_0*\Delta V_0}\text{------------------------------------(3)}$$

SIDO Converter:

The sido converter operates under both CCM Mode and DCM mode. The structure of the proposed SIDO converter is shown below in Fig 6.

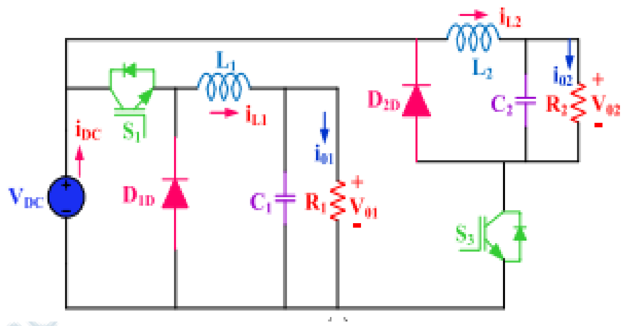

Fig 6: SIDO Converter

It has two switches (S1, S2), two sets of diodes, inductors, capacitors and load. In this, the load voltages are able to be regulated at independent voltages with the help of different duty cycles D1 − D2.

The proposed converter possesses the following advantages:

- It is simple in construction without any operational conditions on duty ratio (D1 > D2 or D2 < D1 or D1 = D2)
- The load voltages are independent to each other.
- No limits or conditions on inductor currents such as iL1 < iL2 or iL1 > iL2.
- There are no issues of cross regulation as the loads are isolated.
- It can be extended to N number of loads.

The buck converter is designed by the following equations:

The calculation of Duty ratio (D) is provided below:

$$D = \frac{Vo}{Vin}\text{ --(4)}$$

The inductor is calculated by the relation given below:

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$$L = \frac{Vo*(Vo-Vin)}{\Delta Io*Fsw*Vin}\text{--(5)}$$

The ripple inductor current is calculated using the following relation:

$$\Delta I_L = 0.2 * I_{in}\text{--(6)}$$

The load side capacitance is calculated by the relation given below:

$$C_0 = \frac{\Delta I_L}{8*f*\Delta V_0}\text{--(7)}$$

The capacitor ripple voltage calculation is provided below.

$$\Delta Voc = 2\%\ of\ Vo\text{----------------------------------(8)}$$

Fuzzy Logic Controller

Fuzzy logic is a way of thinking that closely resembles human reasoning. The tactic imitates how people decide, which involves considering all middle choices in between the digital signals YES and NO. Although fuzzy logic (FL) might not result in accurate reasoning, it is nonetheless useful. The FL's architecture is broken down by modules that convert system inputs into fuzzy sets. Another module that contains rules supplied by the user's IF-THEN statements. a fuzzy inference engine that uses IF-THEN rules and fuzzy interpretation on the inputs to emulate human reasoning. Defuzzification is a different module that converts the fuzzy set acquired by the interfering engine into a crisp value. The membership function operates on sets of variables that are ambiguous. A fuzzy set can be graphically represented and linguistic terms can be quantified using membership functions. Simple model parameters can be utilised because complex functions do not increase output precision. The most common membership function shape is the triangle, which is more common than other forms like the trapezoidal, singleton, and gaussian. Fuzzy thinking has fairly simple mathematical underpinnings.

Table I. Knowledge based rules

E	*D*
NVL	***PS***
NL	***Ps***
NM	***PS***
NS	***PS***
Zero	***PS***
PS	***PM***
PM	***PM***
PL	***PL***
PVL	***PL***

When the error, is negative, the measured voltage is higher than reference voltage[5], then the fuzzy controller will provide Low as output and when the error is positive, the measured voltage is lower than the reference voltage, and then the fuzzy controller increases the duty ratio (D).

III. SIMULATION SETUP & RESULTS

The simulation parameters for the proposed inverter are provided below in Table II:

TABLE II. Simulation Parameters

Input Voltage	230 V
Input power	150W
Switching Frequency	2 KHZ
Inductor	91.1mH
Coupling Capacitor	56μF
Output Capacitor	20mF
Battery voltage	60V
Battery capacity	1.5Ah
DC Motor parameters	48V, 150W, 1500 rpm

The simulation circuit of the proposed system is provided below in Fig 7:

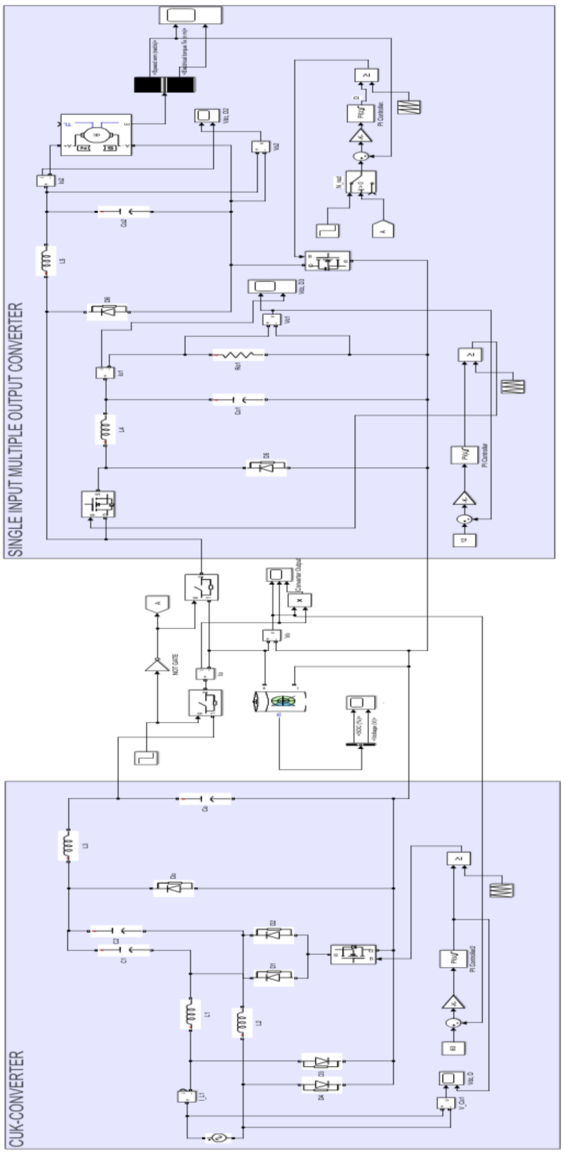

Fig 7: Simulation circuit of proposed EV system

In this, the ac supply of 230V, 50 Hz is provided as input to the modified cuk converter which charges the battery of 60V, 1.5Ah until t=0.5s and after that cuk converter is disconnected as sido converter is connected and the vehicle starts operating. In this, a dc motor load is connected for EV operation and other loads such as lights, music system, etc is provided as load2. The power factor measured from the EV with PI controller is provided below in Fig 8:

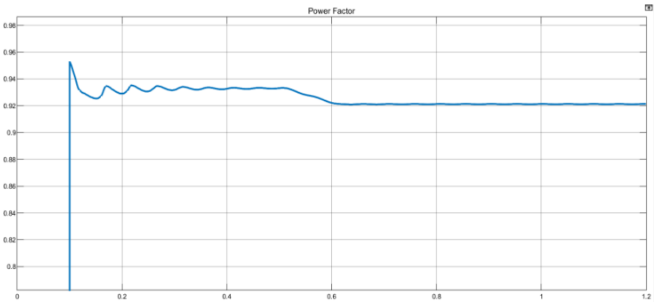

Fig 8: Power factor with PI controller

The power factor with PI controller from the above graph is around 0.93. The battery voltage and %SOC is provided below in Fig 9:

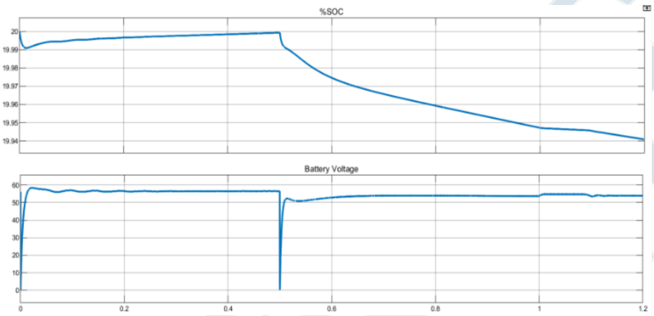

Fig 9: Battery %SOC and voltage of proposed system

In this initially the battery is charging and hence the %SOC increases until t=0.5s and then the battery starts to discharge and hence the %SOC of the battery starts reducing. The dc motor load voltage and current is provided below in Fig 10:

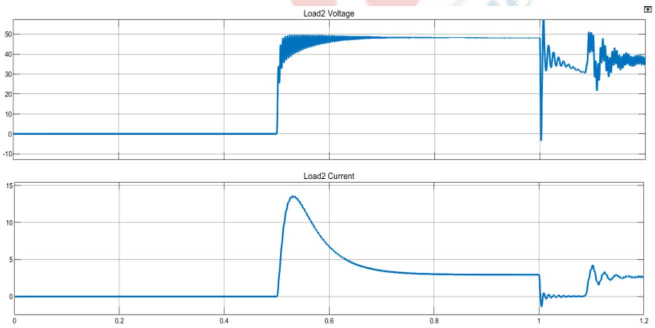

Fig 10: Dc motor Voltage and current

The motor voltage is initially around 50V and it is reduced to 35V at t=1s due to the change in speed reference. The speed reference is changed from 150 rad/s to 100 rad/s at t=1s. The speed and torque of the dc motor is provided below in Fig 11:

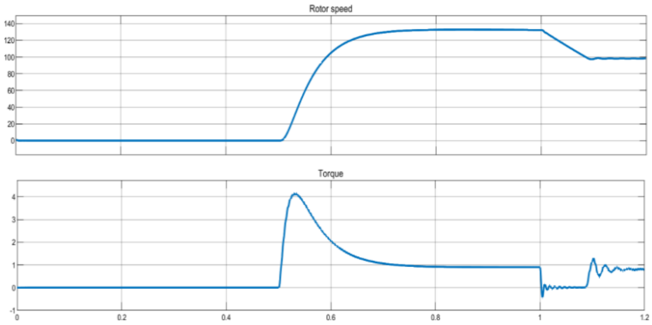

Fig 11: Speed and Torque of dc motor with PI controller

In this after t=0.5s, the motor starts to run and it reached the speed of 132.5 rad/s at t=0.74s and after reference speed changed to 100 rad/s at t=1s, the motor speed reaches 98 rad/s at t=1.09s with PI controller. The other load voltage and current waveforms is provided below in Fig 12:

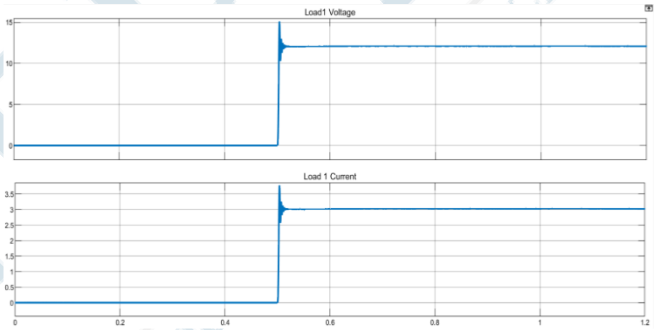

Fig 12: Voltage and current waveforms of other EV loads such as lighting system, music system, etc.

The PI controller is replaced with fuzzy logic controller and the power factor measured with FLC is provided below in Fig 13:

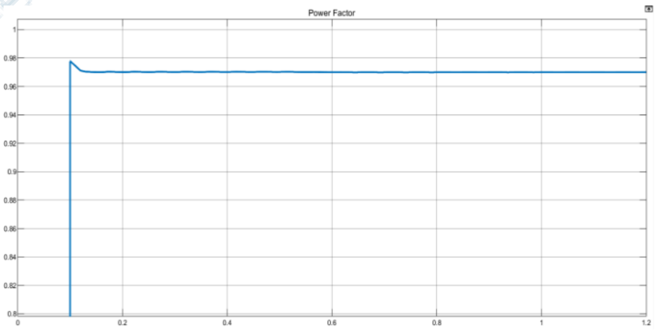

Fig 13: Power factor with fuzzy logic controller

The power factor with FLC from the above graph is around 0.97. The dc motor load voltage and current is provided below in Fig 14.

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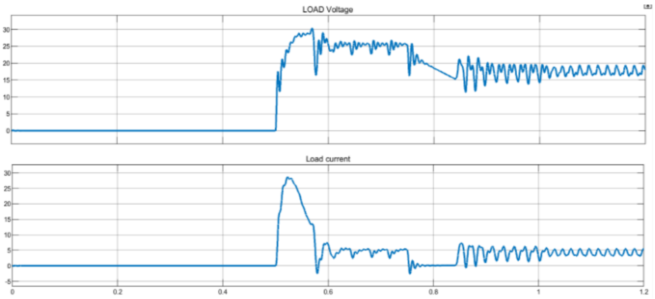

Fig 14: Dc motor Voltage and current with FLC

The motor voltage is initially around 25V and it is reduced to 20V at t=0.75s due to the change in speed reference. The speed reference is changed from 150 rad/s to 100 rad/s at t=0.75s. The speed and torque of the dc motor is provided below in Fig 15.

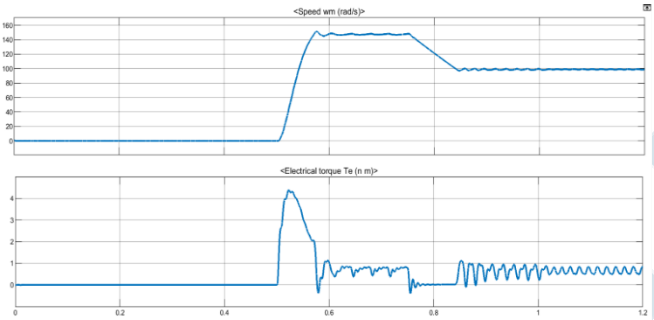

Fig 15. Speed and Torque of dc motor with FLC

In this after t=0.5s, the motor starts to run and it reached the speed of 147.5 rad/s at t=0.585s and after reference speed changed to 100 rad/s at t=0.75s, the motor speed reaches 99 rad/s at t=0.84s with fuzzy logic controller. The performance of the proposed EV is compared with PI and fuzzy logic controllers and tabulated below in Table III.

TABLE III. Comparison of Performance of EV under PI and FLC controllers

Parameters	PI Control				Fuzzy Logic Control			
Power Factor	0.93				0.97			
Motor speed	Ref Speed (Rad/s)	Measured speed (Rad/s)	Steady state error (%)	Settling time (s)	Ref Speed (Rad/s)	Measured speed (Rad/s)	Steady state error (%)	Settling time (s)
	150	132.5	11.6	0.24	150	147.5	1.67	0.085
	100	98	2	0.09	100	99	1	0.09

IV. HARDWARE IMPLIMENTATION

In this, hardware implementation of power factor correction cuk converter is done. the actual ratings will be scaled down to develop the hardware prototype. As can be seen in the below picture the 230V,50HZ single phase supply is parallelly connected with 3 12V,3A Transformers. The secondary side of the transformer is connected in series and 36V,3A supply is produced and injected into cuk converter.

Controller is connected with 12 volts supply, the duty cycle for the controller is set by mentioning the on time and off time. And the signal will be sent to buffer IC ,the IC used here is CD4050 which will help in isolating the signals between controller. The regenerated signals from the buffer IC will reach the Driver IC TLP 250.The Protection circuit for the Driver IC is carefully designed by using current limiting resistor and diodes and capacitors for reverse current blocking, and ripple Reduction.

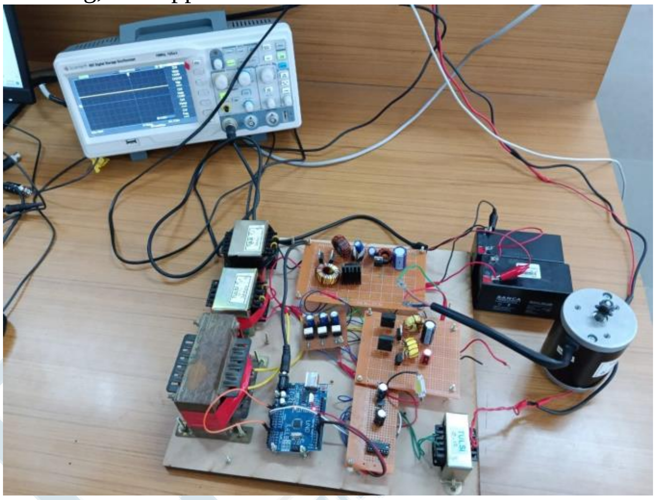

Fig 16: Hardware Implementation of CUK-Converter

In the output side of the Cuk converter the DC power is obtained. Which is charging the 24 V battery .the out from the Cuk converter is shown below.

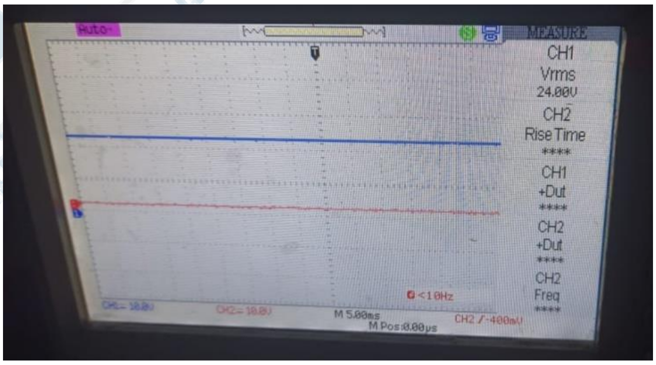

Fig 17: Output from the CUK-Converter

V. CONCLUSION

In this, a modified cuk converter with power factor correction capability is designed for charging the battery of EV and also a sido converter was designed for operating the EV motor and also other EV loads simulataneously. A control circuit with Fuzzy logic controller is designed and the performance is compared with conventional PI controller in terms of power factor, steady state error of speed along with settling time for different motor speeds. The FLC provide better steady state and transient performance of the EV system compared to conventional PI controller.

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