An Isolated Power Factor Corrected Power Supply Utilizing the Transformer Leakage Inductance

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Abstract: The widespread use of electronic devices increases the need for compact power factor corrected power supplies. The use of electronic equipment has increased in last few years. AC rectification is a very inefficient process, resulting in waveform distortion of the current which is drawn from the source. This produces a large spectrum of harmonic signals that may interfere with other equipment. In input rectifier bridge the conventional boost PFC suffers from the high conduction loss This project describes an isolated power factor corrected power supply that utilizes the leakage inductance of the isolation transformer to provide boost inductor functionality. The bulk capacitor is in the isolated part of the power supply allowing for controlled startup without dedicated surge limiting components. A control method based on switch timing and input/output voltage measurements is developed to jointly achieve voltage regulation and input power factor control.

KEYWORDS: DCM-discontinuous conduction mode, CCM - continuous conduction mode, THD - total harmonic distortion, PFC - power factor correction, PF - power factor

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INTRODUCTION

The use of electronic devices from single-phase ac supplies necessitates the increasing use of power factor corrected (PFC) power supplies in many applications including electronic equipment, computer servers, and consumer products. Power factor is the ratio between the useful (true) power (kW) to the total (apparent) power (kVA) consumed by an item of a.c. electrical equipment or a complete electrical installation. It is a measure of how efficiently electrical power is converted into useful work output. The ideal power factor is unity, or one. Anything less than one means that extra power is required to achieve the actual task at hand. PFC power supplies provide low total harmonic distortion(THD) in the current drawn from the line and this is an increasingly important requirement.Power factor correction techniques have been researched widely in the literature and an active PFC using high frequency switching techniques are now commonly used. The overarching principle involves controlling the input current drawn from the mains input to achieve the required current shape for low THD and high power factor. The power supply must provide a regulated dc output voltage and for many applications,galvanic isolation is also required.The basic boost or step-up converter forms the core of most architectures as it has an input inductor that allows input current control to be readily achieved. The well-known flyback converter can be derived from the buck-boost converter, but with a transformer for output voltage isolation Traditionally for PFC supplies, fly back converters have been used for lower power levels (≤100 W). For higher power levels(≥500 W), a separate boost converter for PFC and separate dc to dc converter with transformer isolation for output dc voltage regulation is used.

HOW TO IMPROVE POWER FACTOR

Power factor correction is achieved by the addition of capacitors in parallel with the connected motor or lighting circuits and can be applied at the equipment, distribution board or at the origin of the installation. Static power factor correction can be applied at each individual motor by connecting the correction capacitors to the motor starter. A disadvantage can occur when the load on the motor changes and can result in under or over correction. Static power factor correction must not be applied at the output of a variable speed drive, solid state soft starter or inverter as the capacitors can cause serious damage to the electronic components. Over-correction should not occur if the power factor correction is correctly sized. Typically the power factor correction for an individual motor is based on the non load (magnetizing) power since the reactive load of a motor is comparatively constant compared to actual kW load over compensation should be avoided. Care should be taken when applying power factor correction star/delta type control so that the capacitors are not subjected to rapid on-off-on conditions. Typically the correction would be placed on either the Main or Delta contactor circuits. Power factor correction applied at the origin of the installation consists of a controller monitoring the VAr's and this controller switches capacitors in or out to maintain the power factor better than a preset limit (typically 0.95). Where 'bulk' power factor correction is installed, other loads can in theory be connected anywhere on the network.

A. ACTIVE CORRECTION:

In active power factor correction, we must use an active power factor circuit that forces the AC current to track the AC voltage. One of the most common active PFC circuits is called the boost PFC converter. The boost PFC circuit cycles rapidly between two states, switch closed and switch open. During this states the inductor and capacitor charges and discharge.

B.PASSIVE CORRECTION:

One type of power factor correction (PFC) involves passive correction, where the reactive power of a system is compensated by adding a component that will use an equal but opposite amount of reactive power. For example, if a load is inductive with a reactive power of 1.754 kVAR, then the system would require a capacitive load with a reactive power of 1.754 kVAR to oppose the inductance. This type of power factor correction works well for linear loads on large scales where the cost of the power factor correction system can be absorbed by the size and cost of the overall system. Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as "3.5-inch disk drive".

C. OPERATION OF BOOST CONVERTER:

The boost PFC circuit cycles rapidly between two states. The first state occurs when S1 is closed When in this state, the inductor is being energized by the AC side of the circuit via the rectifier, and thus the inductor current will be increasing. When in this state, the inductor is being energized by the AC side of the circuit via the rectifier, and thus the inductor current will be increasing. At the same time, diode D becomes reverse biased and energy is provided to the load by the capacitor. The second state, which occurs when S1 is open. In this state, the inductor de-energizes as it supplies energy to the load and for recharging the capacitor. The cycling between the two states is done at a high frequency that is at least in the tens of kHz, but is often an order of magnitude (or even more) higher than that. The cycling back and forth between states is done rapidly and in a Equations manner that both maintains a constant output voltage and controls the average inductor current. Since the inductor current is increasing in state 1 and decreasing in state 2, the duty cycle determines the amount of time the inductor current increases versus the amount of time the inductor current decreases. Thus, by varying the duty cycle, the average inductor current can be adjusted. By making this average current track the expected current, you can get a significant improvement in power factor and total harmonic distortion (THD).

PROPOSEDPFC ARCHITECTURE

In this paper, an active PFC power supply is described, whereby the leakage inductance of the high-frequency isolation transformer is used to provide the functionality of the boost inductor. Minimization of the leakage inductance in high frequency isolation transformers is normally desirable in most dc to dc converters, although resonant and soft switching architectures do use a controlled amount of leakage inductance for the purpose of reducing switching losses. The use of a controlled amount of leakage inductance is proposed in this paper to eliminate the need for two separate magnetic components in the two-stage PFC converter and instead uses one magnetic component to achieve both the power factor correction and galvanic isolation. Inrush current on startup can also be controlled by implementing a soft start strategy whereby the large bulk capacitor is initially charged up in a controlled manner. Bidirectional core excitation is used, with part of the energy transferred via transformer action, and part stored in the transformer leakage inductance. The described architecture provides a useful technique at power levels above those suitable for single-stage flyback type converters. The technique lends itself to the adoption of wide band gap semiconductor devices with hard switching .Typically applications might include LED lighting, electronic equipment, server power supplies, and on-board chargers for electric vehicle.

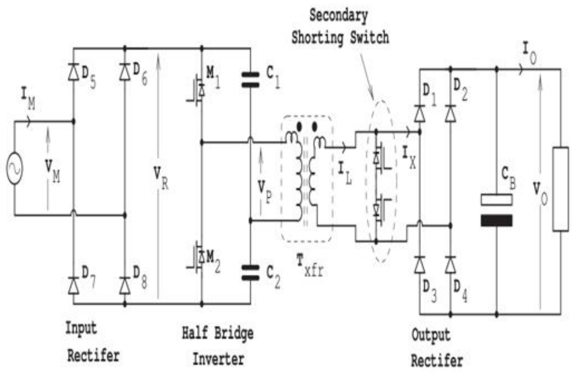


Fig.01 Circuit diagram of the proposed power supply architecture

The circuit diagram of the proposed power supply. A conventional four diode full wave rectifier rectifies the input ac source voltage producing a voltage VR. This voltage is inverted to the high frequency fs with a half-bridge inverter before being applied to a high-frequency transformer. The half-bridge inverter consists of the two switches M1 and M2operated out of phase with a 50% duty cycle at the switching frequency fs and the capacitive divider formed by C1 and C2. The capacitors C1 and C2 prevent dc current flowing through the transformer primary and causing saturation problems. The values of C1 and C2 are chosen sufficiently small, such that at the mains frequency fAC and low power level, they allow the rectifier output voltage VR to follow the input mains waveform elope. However, at the switching frequency, their values are sufficiently large to act as fixed voltage sources and not resonate with the transformer inductances or load.For the circuit of Fig. 1. The mains input voltage is VM (t) =√2VAC sin(2πfACt), with VAC being the rms input voltage and VR(t) being the input voltage fully rectified. The transformer primary voltage VP (t) switches at the high frequency rate fs,but with an amplitude of half VR(t), due to the half-bridge configuration. The symbol for the transformer in Fig. 3.1 is drawn to emphasize that the transformer leakage inductance is used in the circuit rather than the usual case whereby leakage inductance is minimized as much as possible. The key to the operation of the circuit is the bidirectional secondary shorting switch.

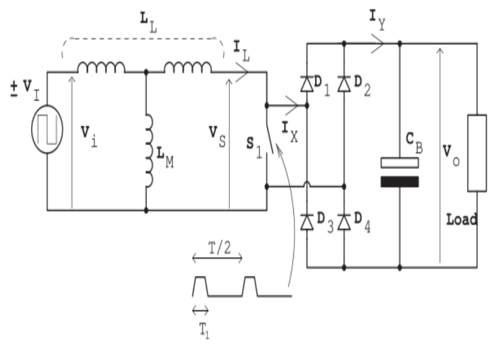


Fig.02 Simplified circuit model for the proposed power supply

THEORY OF OPERATION

Fig. 02 shows a simplified circuit model for the proposed power supply. Assuming the switching frequency of the converter is very high compared to the ac source frequency, the input to the transformer can be considered to be essentially a 50% duty cycle square wave with period T and peak amplitude ±VI . The model in Fig. 3.2 is referenced to the secondary side of the transformer and the voltage amplitude into the transforme rmodel is the primary voltage VP (t) multiplied by the turns ratio of the transformer, orat time t = kT .inductance LM has little effect on the operation of the circuit other than to add a magnetizing current to the input source. Simulations show that magnetizing currents significantly less (a factor of 1 5 × or less), than the currents being transferred, have little impact on the circuit overall functionality. The total leakage inductance of the transformer is denoted as LL and the current flowing out of the transformer secondary winding is denoted as IL(t). The operation of the system is essentially that of a step upor boost converter and is based around the timing of shorting switch S1 in Fig. 3.2. At the beginning of a switching cycle, the input voltage switches to +VI (dropping the [kT] for notation for clarity) and simultaneously the shorting switch S1 is turned ON.

$$T_1 = \sqrt{G_M T L_L \left(\frac{V_O - V_I}{V_O}\right)}.$$

The current IL(t) in the leakage inductance LL rises linearly while the switch S1 is ON. When the switch S1 is turned OFF, the current in the leakage inductance is forced through the rectifier diode bridge formed by D1, D2, D3, and D4, and into the capacitor CB and system load, and the current in the leakage inductance falls

$$I_L^* = \frac{T_1^2}{TL_L}\left(\frac{V_I V_O}{V_O - V_I}\right).$$

.

After a period of T2 , the input voltage changes sign to −VI and the same operation occurs, except for a change in the sign of the inductor current. Two distinct operation modes of the circuit can be identified depending on whether the leakage inductance current starts at zero and returns to zero before timeT2, denoted as the discontinuous conduction mode (DCM), or when the leakage inductance current starts the cycle with a nonzero (negative) value, retains a nonzero (positive) value at time T2 and returns to a nonzero (negative) value at the end of the cycle (time T), denoted as the continuous conduction mode(CCM). To achieve unity power factor, the circuit needs to be operated in such a manner as to control the input current drawn from the supply.

$$I_M = \frac{1}{2}\frac{N_s}{N_p} I_L^*$$

Discontinuous Conduction Mode

The input voltage Vi(t), the secondary voltage VS (t), the leakage inductor current IL(t), and the current in to and out of the output rectifier IX (t) and IY (t) as well as the switch current IS 1(t), for the circuit operating in DCM. With the shorting switch S1 closed, the leakage inductor current IL(t)rises from zero to the value +IP over the set period T1, thus When the shorting switch S1 opens, the inductor current falls back to zero over a period T2 with the relationship The sum of the periods must be less than the half period T/2to ensure operation in the DCM or (3.4) The average input current to the transformer model (ignoring the magnetizing inductance) over the period T/2 can then be calculated as follows: And combining with and the average input current is that. The actual input current from the ac source is a scaled versionof this current and isWith any contribution from the magnetizing inductance averaging to zero over each T period. It is apparent by considering and, that achieving unity power factor in the input source is equivalent to controlling the current value I∗L to be directly proportional to VI . Denoting the constant of proportionality as GM , or IL∗ = GM VI , then substituting in and rearranging yields the equation

$$V_I[kT] = \left| V_P(kT)\frac{N_s}{N_p} \right|$$

The equation shows that given a constant of proportionality as GM , the required time period T1 can be calculated by knowledge of the system parameters LL and T , measurement of the output voltage VO and calculating VI by measurement of the rectified input source voltage and scaling by a factor of 1 2 NN sp 3.3.2 Continuous Conduction Mode shows the input voltage Vi(t), the secondary voltage VS (t), the leakage inductor current IL(t), and the current into and out of the output rectifier IX (t) and IY (t) as well as the switch current IS 1(t), for the circuit operating in CCM.

When the shorting switch S1 opens, the inductor current falls back to zero over a period T2 with the relationship

$$I_P = (V_O - V_I)T_2/L_L$$

The sum of the periods must be less than the half period T/2 to ensure operation in the discontinuous conduction mode or $T_1 + T_2 \leq \frac{T}{2}$.

The average input current to the transformer model (ignoring the magnetizing inductance) over the period T/2 can then be calculated as $I_L^* = \frac{1}{2} I_P \frac{T_1 + T_2}{\frac{T}{2}}$

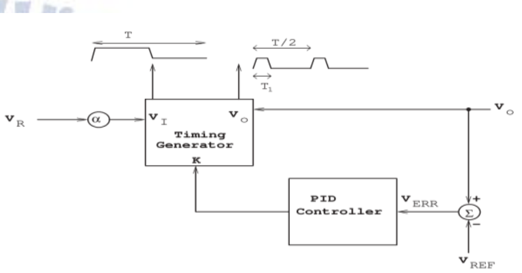
The actual input current from the AC source is a scaled version of this current and is $I_M = \frac{1}{2}\frac{N_s}{N_P} I_L^*$ with any contribution from the magnetizing inductance averaging to zero over each T period. It is apparent by considering eqn. 1 and eqn. 7, that achieving unity power factor in the input source is equivalent to controlling the current value IL* to be directly proportional to VI . Denoting the constant of proportionality as GM, or IL* = GMV1 , then substituting in eqn. 6 and rearranging yields the equation . The control objective for the power supply is to provide a constant output voltage and unity input power factor. This requires measurement of the output voltage and adjustment of the input current through the GM factor defined in section III-A However, calculating the time parameter T1 in section III-A and III-B also requires knowledge of the parameter LL, the leakage inductance, which may not be accurately known

POWER SUPPLY CONTROL CIRCUIT

The control objective for the power supply is to provide a constant output voltage and unity input power factor. This requires measurement of the output voltage and adjustment of the input current through the GM factor defined in section III-A. However, calculating the time parameter T1 in section III-A and III-B also requires knowledge of the parameter LL, the leakage inductance, which may not be accurately known. Therefore a new control parameter K is defined as $K = \frac{G_M L_L}{T}$.

FEEDBACK CONTROL FOR THE POWER SUPPLY

The feedback loop can then be used to control the power supply. The power supply output voltage VO is measured and compared to a reference voltage VREF to produce an output voltage error VERR = VO − VREF. This error voltage is used by a PID controller with dynamics below the input AC frequency fAC to adjust the variable K to control the output voltage VO .The variable K, is used in the timing generator to generate the inverter timing and the secondary shorting period T1 twice per sample period T .



The timing generator uses the measured power supply output voltage VO, and a scaled version of the input rectifier voltage VR as VI = (1/2)(Ns/Np)VR. Using K, VI and VO, the timing generator evaluates the result is true,[14]the DCM is selected and eqn. 17 is used to calculate the time period T1. Otherwise, the CCM is selected and eqn. is used to calculate the time period .

RESULTS AND DISCUSSION

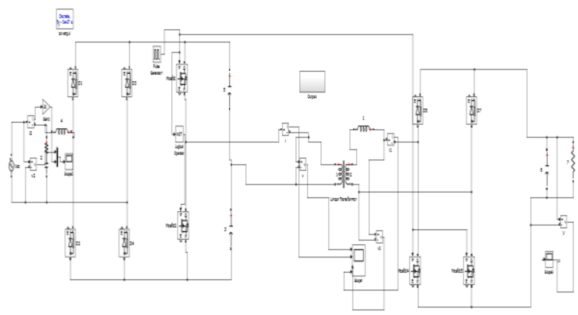


Fig.03 Simulink diagram of Proposed System Power Factor

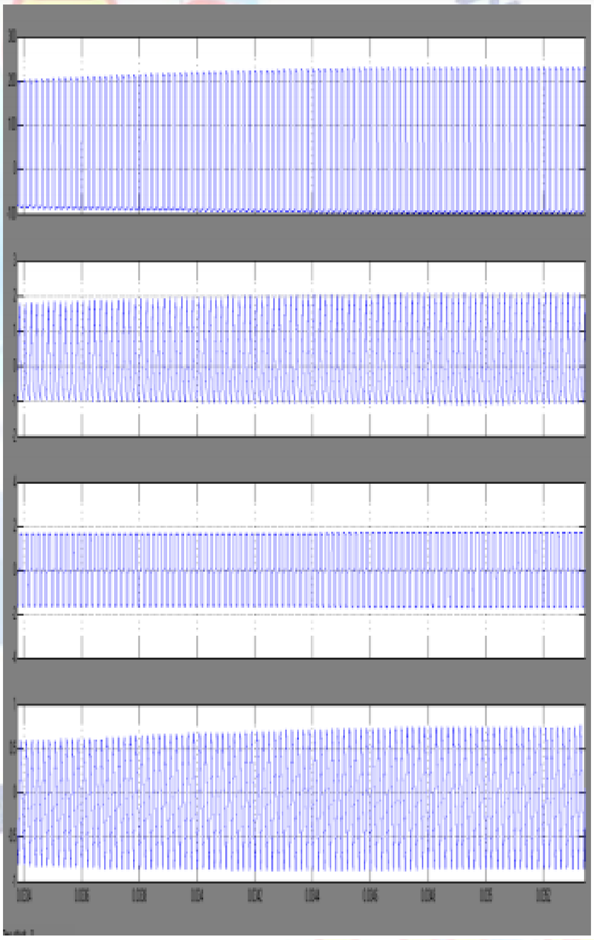


Fig.04 Simulation waveforms at 300 W operation over a complete line cycle,input ac voltage (VAC) and current (IAC) and transformer primary voltage (VP) and current (IP)

Measured waveforms of the line input voltage and current and transformer primary voltage and current are shown in Fig. 5.2 over a full line cycle. Zoomed in waveforms of the transformer primary voltage and current and secondary voltage and current are shown in Fig. 5.3 (DCM) and Fig. 5.4 (CCM)and confirm the desired operation. The effect of finite values ofbus capacitors C1 and C2 can be seen in the primary voltage waveform of Fig.04 as a drop in the voltage rather than an ideal square wave.

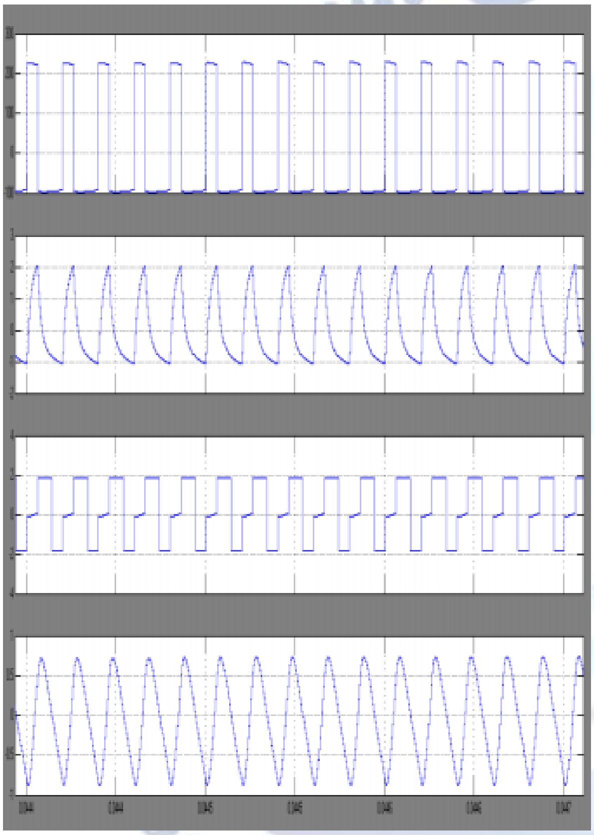


Fig.05 Measured waveforms at 300 W operation, 1.5 ms from zero crossing and operating in DCM mode. Transformer primary voltage (VP) and current(IP) and secondary voltage (VS) and current (IS)

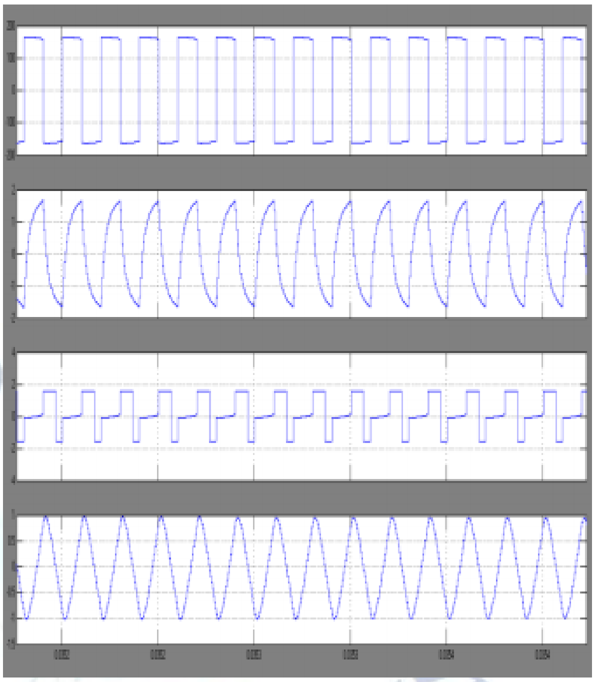


Fig06.Simulation waveforms at 300 W operation, 5 ms from zero crossing and operating in CCM mode .Transformer primary voltage (VP) and current(IP) and secondary voltage (VS) and current (IS).

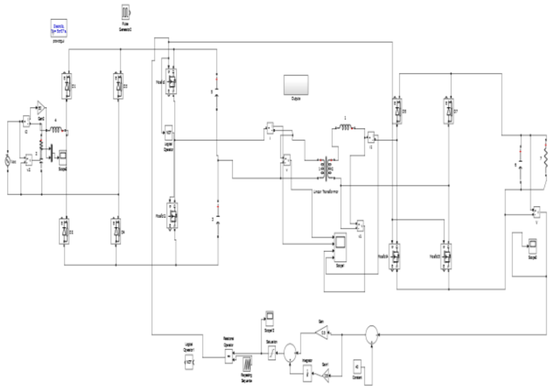


Fig.07

Simulink diagram of Proposed System Power Factor Corrected AC–DC power conversion with Induction Motor drive

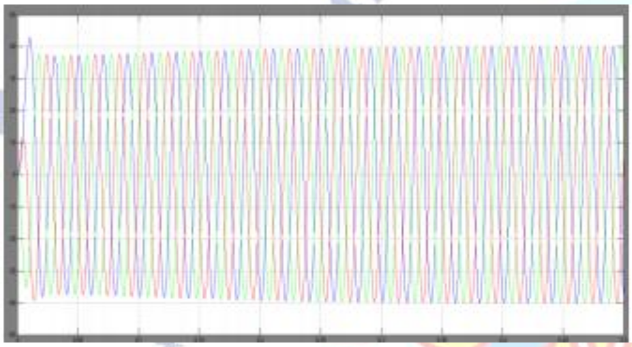


Fig.08 Simulation waveforms of Induction motor drive stator current characteristics

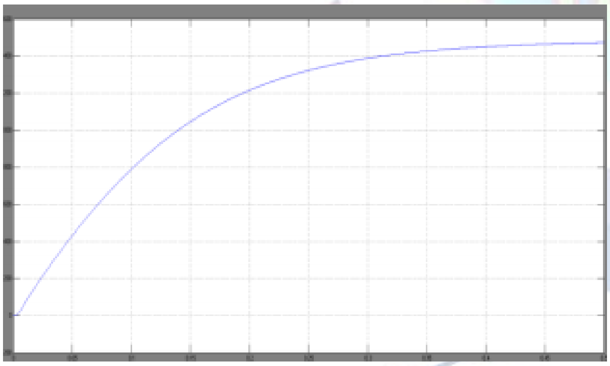


Fig.09 Simulation waveforms of Induction motor drive speed characteristics

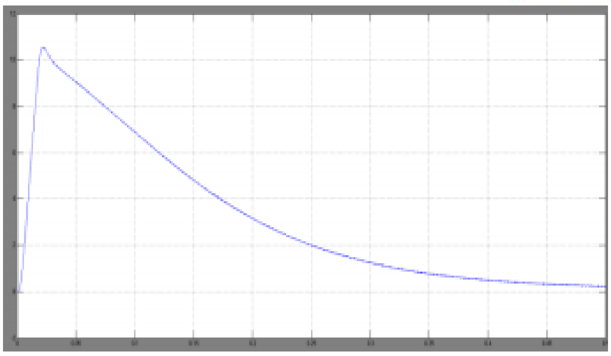


Fig.10 Simulation waveforms of Induction motor drive Torque characteristics

CONCLUSION

This paper describes an isolated ac/dc power supply using the leakage inductance of the isolation transformer to achieve active power factor correction. The proposed with induction motor drive architecture allows for a compact lightweight power supply for power levels above that of flyback type PFC supplies. The principle of operation with two conduction modes is described and a timing based control method is developed for the power factor control. Measurements confirm the active power factor correction functionality with high power factor and low THD. The proposed with induction motor drive power supply architecture is scalable and it should be feasible to extend the power capability of the proposed circuit to 500 W or more. Further variations on the principle canbe adopted, such as universal input voltage operation, full bridge input inverter, zero current switching, synchronous rectification,interleaved designs, and so forth. The proposed architecture provides an additional option for the designers of PFC isolated supplies .And also verified the Induction motor characteristics.

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