International Journal for Modern Trends in Science and Technology, 7(03): 107-114, 2021

ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0703019
Available online at: http://www.ijmtst.com/vol7issue03.html

An Active Power Factor Corrected Power Supply fed Induction Motor Drive by Controlling the Leakage Inductance for Transformer with Soft Switching Strategy

Jagata Kotasatyavathi[1] | Guduru Ravi Kumar[2]

[1]PG Scholar, Department of EEE, Priyadarshini Institute of Technology & Science, Chintalapudi, India.
[2]Associate Professor & HOD, Department of EEE, Priyadarshini Institute of Technology & Science, Chintalapudi, India.

To Cite this Article
Jagata Kotasatyavathi and Guduru Ravi Kumar, "An Active Power Factor Corrected Power Supply fed Induction Motor Drive by Controlling the Leakage Inductance for Transformer with Soft Switching Strategy", *International Journal for Modern Trends in Science and Technology*, Vol. 07, Issue 03, March 2021, pp.: 107-114.

Article Info
Received on 03-February-2021, Revised on 02-March-2021, Accepted on 05-March-2021, Published on 12-March-2021.

ABSTRACT

Nowadays the use of electronic equipment finds a progressive development in the modern world. Hence it becomes a mandate to check whether the harmonic content of line current of any electronic device which is connected to the ac supply meets the appropriate standards. This demand is satisfied by implementing the Power Factor Correction (PFC) circuit in order to make the input current to be in sinusoidal in nature and in-phase with the input voltage. Numerous solutions are available to make the line current almost sinusoidal. This paper 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: *AC–DC power conversion, power factor correction, transformer leakage inductance.*

INTRODUCTION

The widespread use of electronic devices from single-phase ac supplies necessitates thincreasing use of power factorcorrected (PFC) power supplies in many applications includingelectronic equipment, computer servers, and consumer products. 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 researchedwidely in the literature [1], [2] and an active PFC using highfrequency switching techniques [3] are now commonly used.

The overarching principle involves controlling the input currentdrawn from the mains input to achieve the required current shapefor 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 [4] forms the core ofmost architectures as it has an input inductor that allows inputcurrent control to be readily achieved. The well-known flybackconverter can be derived from the buck-boost converter, but witha transformer for output voltage isolation [4].

Traditionally for PFC supplies, fly back converters have beenused for lower power levels (≤100 W). For higher power levels(≥500 W), a separate boost converter for PFC and separate dcto dc converter with transformer isolation for output dc voltageregulation is used.

PROPOSED PFC 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 theboost inductor. Minimization of the leakage inductance in highfrequency isolation transformers is normally desirable in mostdc to dc converters, although resonant and soft switching architectures do use a controlled amount of leakage inductance [17]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 insteaduses one magnetic component to achieve both the power factorcorrection and galvanic isolation.Inrush current on startup can also be controlled by implementing a soft start strategy whereby the large bulk capacitor isinitially charged up in a controlled manner.

Bidirectional core excitation is used, with part of the energy transferred via transformer action, and part stored inthe transformer leakage inductance. The described architectureprovides a useful technique at power levels above those suitablefor single-stage flyback type converters.

The technique lends itself to the adoption of wide band gapsemiconductor devices [18] with hard switching [19], [20]. Typically applications might include LED lighting, electronic equipment, server power supplies, and on-board chargers for electricvehicles.

Proposed Architecture

The circuit diagram of the proposed power supply is shownin Fig. 3.1. A conventional four diode full wave rectifier rectifiesthe input ac source voltage producing a voltage VR. This voltageis inverted to the high frequency fs with a half-bridge inverterbefore being applied to a high-frequency transformer Txfr. Thehalf-bridge inverter consists of the two switches M1 and M2operated out of phase with a 50% duty cycle at the switchingfrequency fs and the capacitive divider formed by C1 and C2.

The capacitors C1 and C2 prevent dc current flowing throughthe transformer primary and causing saturation problems. Thevalues of C1 and C2 are chosen sufficiently small, such that atthe mains frequency fAC and low power level, they allow therectifier output voltage VR to follow the input mains waveformenvelope. However, at the switching frequency, their values aresufficiently large to act as fixed voltage sources and not resonatewith 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 andVR(t) being the input voltage fully rectified. The transformerprimary voltage VP (t) switches at the high frequency rate fs,but with an amplitude of half VR(t), due to the half-bridgeconfiguration.

The symbol for the transformer in Fig. 3.1 is drawn to emphasize that the transformer leakage inductance is used in thecircuit rather than the usual case whereby leakage inductance isminimized as much as possible. The key to the operation of thecircuit is the bidirectional secondary shorting switch shown inFig. 3.1 [21].

THEORY OF OPERATION

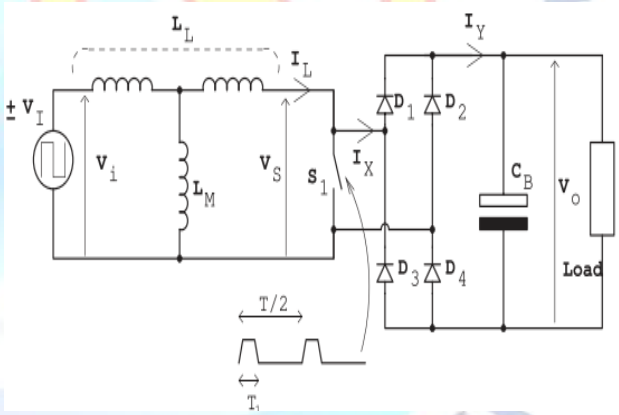


Fig. 2.2.Simplified circuit model for the proposed power supply.

Fig. 2.2 shows a simplified circuit model for the proposed powersupply. Assuming the switching frequency of the converter isvery high compared to the ac source frequency, the input tothe transformer can be considered to be essentially a 50% dutycycle square wave with period T and peak amplitude ±VI . The model in Fig. 3.2 is referenced to the secondary side ofthe transformer and the voltage amplitude into the transformermodel is the primary voltage VP (t) multiplied by the turns ratioof the transformer, orat time t = kT .

$$V_I[kT] = \left| V_P(kT)\frac{N_s}{N_p} \right| \quad (2.1)$$

The operation of the circuit is based on the assumption that thetransformer magnetizing

inductance LM has little effect on theoperation of the circuit other than to add a magnetizing currentto the input source. Simulations show that magnetizing currentssignificantly 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 denotedas LL and the current flowing out of the transformer secondarywinding 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, theinput voltage switches to +VI (dropping the [kT] for notationfor clarity) and simultaneously the shorting switch S1 is turnedON. The current IL(t) in the leakage inductance LL rises linearlywhile the switch S1 is ON. When the switch S1 is turned OFF, thecurrent in the leakage inductance is forced through the rectifierdiode bridge formed by D1, D2, D3, and D4, and into thecapacitor CB and system load, and the current in the leakageinductance falls. After a period of T2 , the input voltage changessign to −VI and the same operation occurs, except for a changein the sign of the inductor current. Two distinct operation modesof the circuit can be identified depending on whether the leakageinductance current starts at zero and returns to zero before timeT2, denoted as the discontinuous conduction mode (DCM), orwhen the leakage inductance current starts the cycle with anonzero (negative) value, retains a nonzero (positive) value attime T2 and returns to a nonzero (negative) value at the end ofthe cycle (time T), denoted as the continuous conduction mode(CCM). To achieve unity power factor, the circuit needs to be operatedin such a manner as to control the input current drawn from thesupply. The two operating modes are now discussed in detail torelate the input current drawn to the timing period T1.

Discontinuous Conduction Mode

Fig. 3.3(a) shows the input voltage Vi(t), the secondary voltageVS (t), the leakage inductor current IL(t), and the current intoand out of the output rectifier IX (t) and IY (t) as well as theswitch current IS 1(t), for the circuit operating in DCM. Withthe shorting switch S1 closed, the leakage inductor current IL(t)rises from zero to the value +IP over the set period T1, thus

$$I_P = V_I T_1 / L_L. \tag{3.2}$$

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

$$I_P = (V_O - V_I) T_2 / L_L. \tag{3.3}$$

The sum of the periods must be less than the half period T/2to ensure operation in the DCM or

$$T_1 + T_2 \leq \frac{T}{2}. \tag{3.4}$$

The average input current to the transformer model (ignoringthe magnetizing inductance) over the period T/2 can then becalculated as follows:

$$I_L^* = \frac{1}{2} I_P \frac{T_1 + T_2}{\frac{T}{2}} \tag{3.5}$$

And combining with (2) and (3), the average input current is

$$I_L^* = \frac{T_1^2}{T L_L} \left(\frac{V_I V_O}{V_O - V_I} \right). \tag{3.6}$$

The actual input current from the ac source is a scaled versionof this current and is

$$I_M = \frac{1}{2} \frac{N_s}{N_p} I_L^* \tag{3.7}$$

With any contribution from the magnetizing inductance averaging to zero over each T period.

It is apparent by considering (1) and (7), that achieving unitypower factor in the input source is equivalent to controlling thecurrent value I∗L to be directly proportional to VI . Denotingthe constant of proportionality as GM , or IL∗ = GM VI , thensubstituting in (6) and rearranging yields the equation

$$T_1 = \sqrt{G_M T L_L \left(\frac{V_O - V_I}{V_O} \right)}. \tag{3.8}$$

The equation shows that given a constant of proportionality asGM , the required time period T1 can be calculated by knowledgeof the system parameters LL and T , measurement of the outputvoltage VO and calculating VI by measurement of the rectifiedinput source voltage and scaling by a factor of 1 2 NN sp

3.3.2 Continuous Conduction Mode

Fig. 3.3(b) shows the input voltage Vi(t), the secondary voltageVS (t), the leakage inductor current IL(t), and the current intoand out of the output rectifier IX (t) and IY (t) as well as theswitch current IS 1(t), for the circuit operating in CCM. Withthe shorting switch S1 closed, the leakage inductor current IL(t)rises from the value −IE to the value +IP over the set periodT1, thus

$$I_P + I_E = V_I T_1 / L_L. \tag{3.9}$$

When the shorting switch S1 opens, the inductor current fallsback to +IE over a period T2 = T/2 − T1 with the relationship

$$I_P - I_E = (V_O - V_I)T_2/L_L. \tag{3.10}$$

The average input current to the transformer model (ignoringthe magnetizing inductance) over the period T/2 can then becalculated as follows:

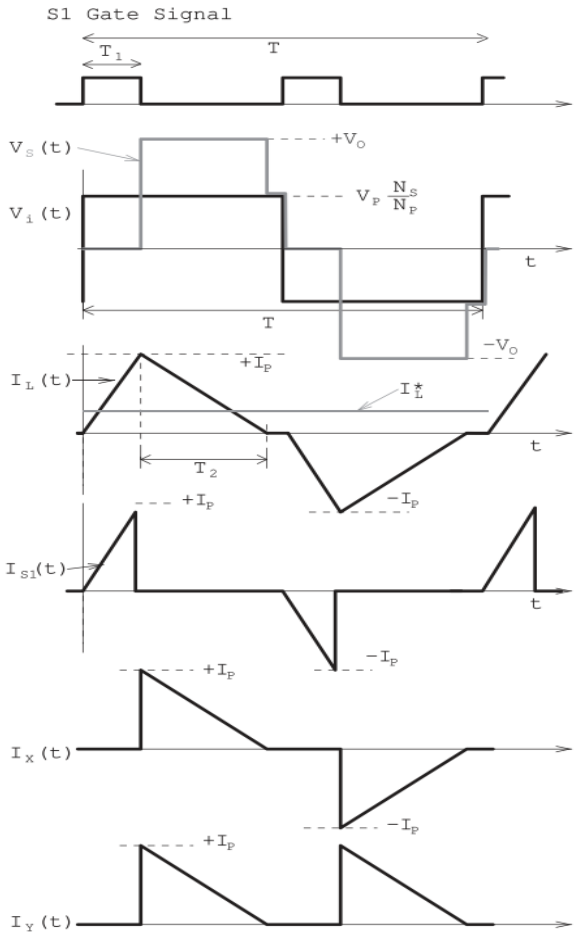
$$I_L^* = \frac{\frac{1}{2}(I_P - I_E)T_1 + \frac{1}{2}(I_P + I_E)T_2}{\frac{T}{2}} \tag{3.11}$$

And combining with (9) and (10), the average input current canbe shown as

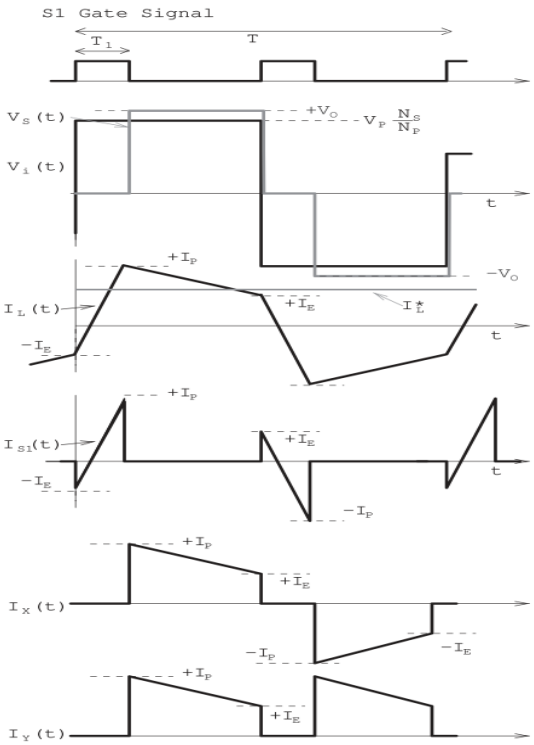
$$I_L^* = \left(T_1\frac{T}{2} - T_1^2\right)\frac{V_O}{TL_L}. \tag{3.12}$$

With I∗L = GM VI , then substituting in (12) and rearrangingyields the equation

$$T_1 = \frac{T}{4}\left(1 - \sqrt{1 - \frac{16G_M L_L V_I}{TV_O}}\right). \tag{3.13}$$



(a) Discontinuous conduction mode.



(b) Continuous conduction mode.

Fig. 3.3 Idealized waveforms. (a) Discontinuous conduction mode. (b) Continuous conduction mode.

Power Handling Capability

The power capability of converter is determined by the maximum value of GM supported, which is limited by the requirement for (13) to result in a real number. This requiresthe argument under the square root to be non-negative, and hence

$$\frac{16G_{M\max}L_L V_I}{TV_O} \le 1$$

$$P_{\max} = \frac{1}{2}G_{M\max}V_{I\max}^2 \text{ of}$$

$$P_{\max} \le \frac{V_{AC}\frac{N_s}{N_p}V_O}{32\sqrt{2}f_s L_L}. \tag{3.14}$$

This equation can be used as a basis for converter design asdemonstrated by the prototype example in Section V. Themaximum peak current in the leakage inductor during the CCMcan be calculated as follows:

$$I_{P\max} = \frac{V_O T}{8L_L} \tag{3.15}$$

And the transformer must be designed to handle this peakcurrent without saturation.

POWER SUPPLY CONTROL

The control objective for the power supply is to provide aconstant output voltage and unity input power factor. This requires measurement of the output voltage and adjustment of theinput current

through the GM factor defined in Section III-A.However, calculating the time parameter T1 in Section III-A andIII-B also requires knowledge of the parameter LL, the leakage

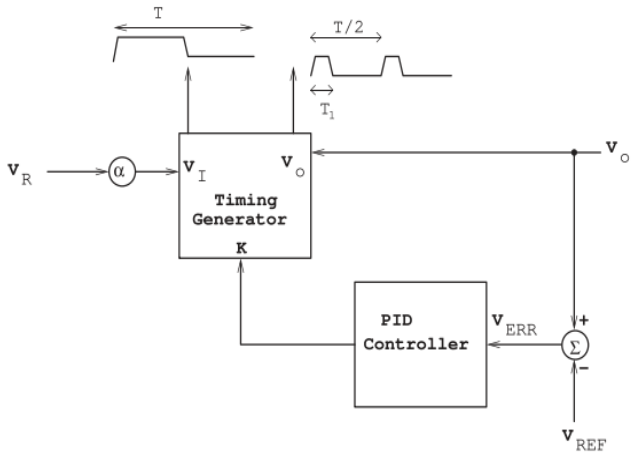


Fig. 3.4 Feedback control for the power supply.

Inductance, which may not be accurately known. Therefore anew control parameter K is defined as follows:

$$K = \frac{G_M L_L}{T} \tag{3.16}$$

And K is used for control rather than GM . Substituting into (8)and (13) results in the required calculations for DCM as

$$T_1 = T\sqrt{K\left(\frac{V_O - V_I}{V_O}\right)} \tag{3.17}$$

And CCM as

$$T_1 = \frac{T}{4}\left(1 - \sqrt{1 - \frac{16KV_I}{V_O}}\right). \tag{3.18}$$

It can further be shown that the boundary condition of (4) canbe written as follows:

$$V_O(1 - 4K) \geq V_I. \tag{3.19}$$

The feedback loop of Fig. 3.4 can then be used to control thepower supply. In Fig. 3.4, the power supply output voltage VO ismeasured and compared to a reference voltage VREF to producean output voltage error VERR = VO − VREF. This error voltageis used by a PID controller with dynamics below the input acfrequency fAC to adjust the variable K to control the outputvoltage VO .

The variable K, is used in the timing generator to generatethe inverter timing and the secondary shorting period T1 twiceper sample period T. The timing generator uses the measuredpower supply output voltage VO , and a scaled version of theinput rectifier voltage VR as VI = 1 2 NN spVR. Using K, VI , andVO , the timing generator evaluates the condition in (3.19) andif the result is true, the DCM is selected and (3.17) is used tocalculate the time period T1. Otherwise, the CCM is selectedand (3.18) is used to calculate the time period T1.

RESULTS AND DISCUSSION

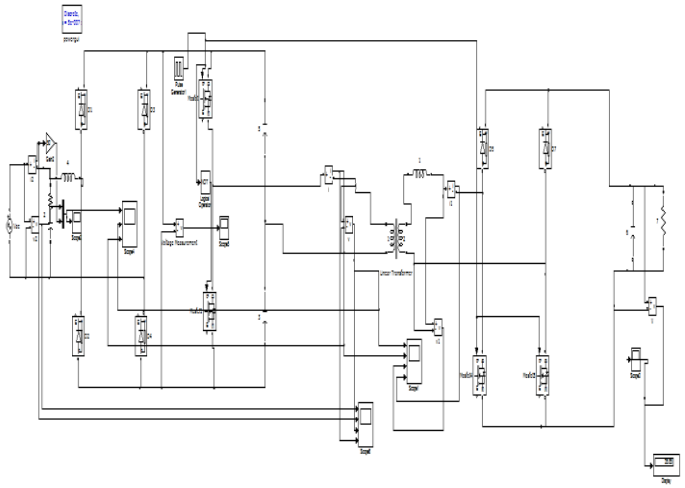


Fig 5.1 Simulink diagram of Proposed SystemPower Factor CorrectedAC–DC power conversion

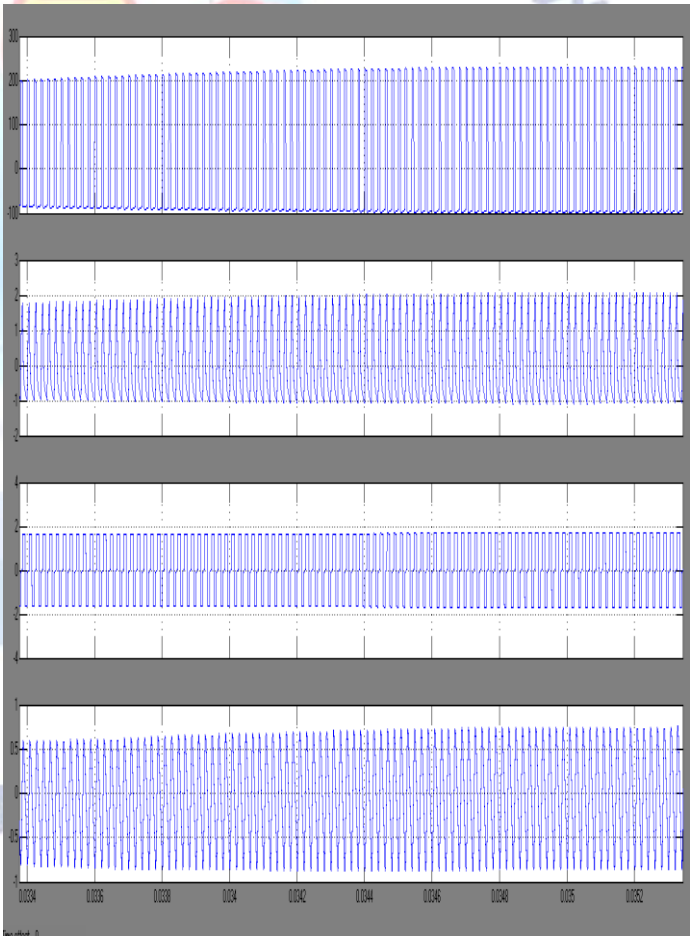


Fig. 5.2.Simulation waveforms at 300 W operation over a complete line cycle,input ac voltage (VAC) and current (IAC) and transformer primary voltage (VP) and current (IP)

Measured waveforms of the line input voltage andcurrent and transformer primary voltage and current are shown in Fig. 5.2 over a full line cycle. Zoomed in waveforms of thetransformer 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. 5.4 as a drop in the voltage rather than anideal square wave.

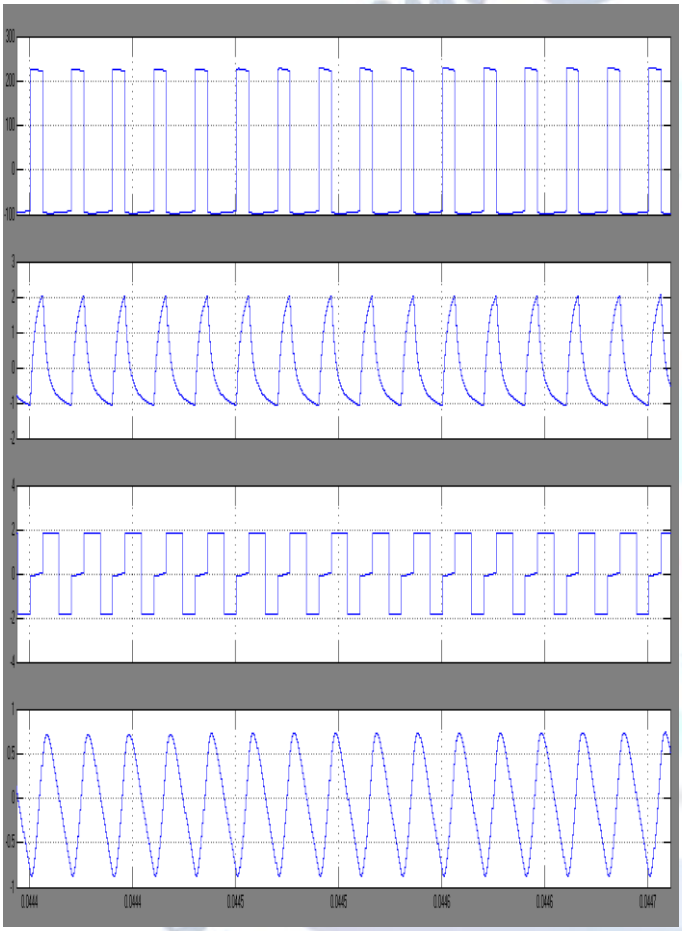


Fig. 5.3. Measured waveforms at 300 W operation, 1.5 ms from zero crossingand operating in DCM mode. Transformer primary voltage (VP) and current(IP) and secondary voltage (VS) and current (IS).

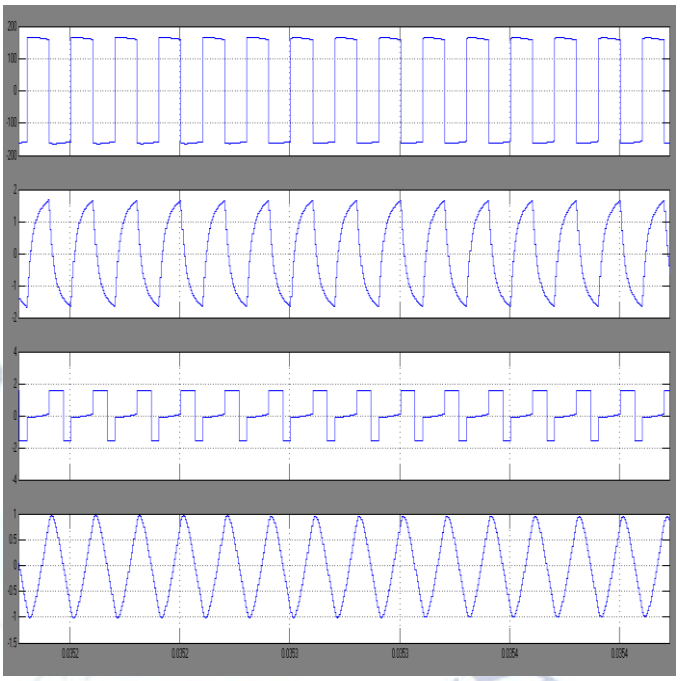


Fig. 5.4.Simulation waveforms at 300 W operation, 5 ms from zero crossingand operating in CCM mode.Transformer primary voltage (VP) and current(IP) and secondary voltage (VS) and current (IS).

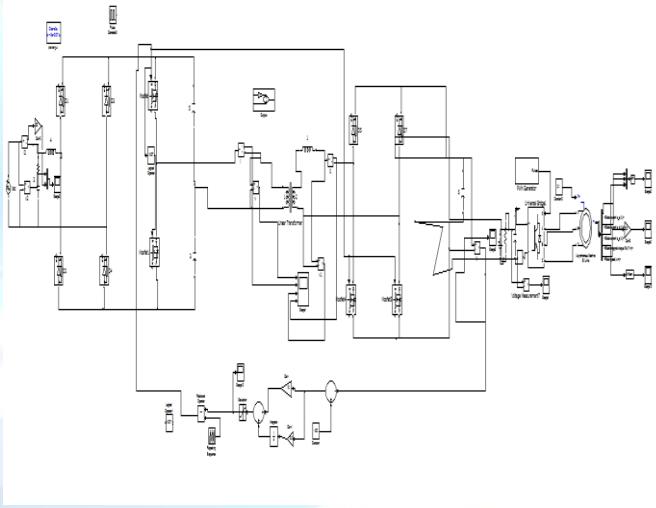


Fig 5.5 Simulink diagram of Proposed SystemPower Factor CorrectedAC–DC power conversion with Induction Motor drive

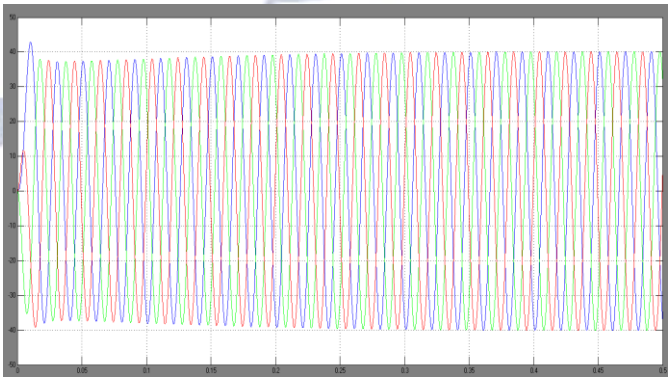


Fig 5.6 Simulation waveforms of Induction motor drive stator current characteristics

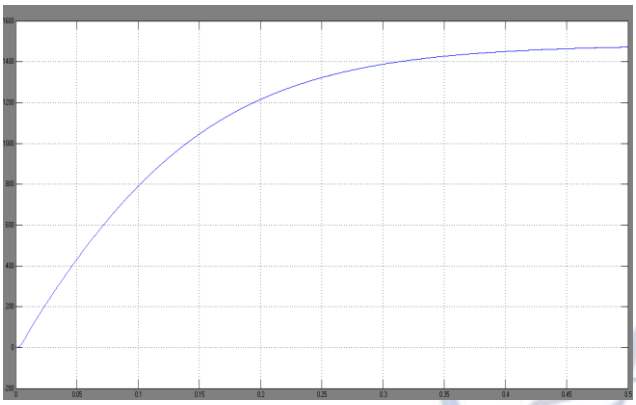


Fig 5.7 Simulation waveforms of Induction motor drive speed characteristics

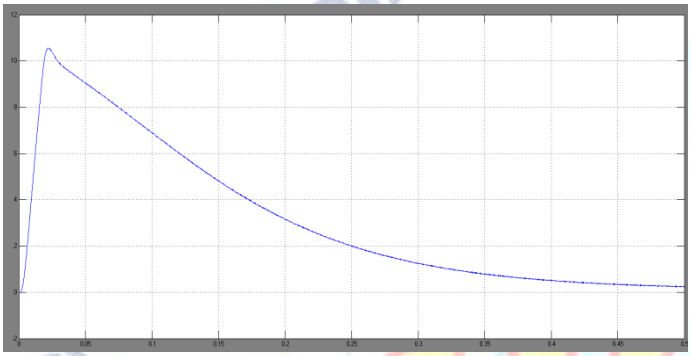


Fig 5.7 Simulation waveforms of Induction motor drive Torque characteristics

CONCLUSION

This paper describes an isolated ac/dc power supply usingthe leakage inductance of the isolation transformer to achieveactive power factor correction. The proposed with induction motor drive architecture allowsfor a compact lightweight power supply for power levels abovethat of flyback type PFC supplies. The principle of operationwith two conduction modes is described and a timing basedcontrol method is developed for the power factor control. Measurements confirmthe active power factor correction functionality with high powerfactor and low THD.

The proposed with induction motor drive power supply architecture is scalable and itshould be feasible to extend the power capability of the proposedcircuit to 500 W or more. Further variations on the principle canbe adopted, such as universal input voltage operation, full bridgeinput inverter, zero current switching, synchronous rectification,interleaved designs, and so forth. The proposed architectureprovides an additional option for the designers of PFC isolatedsupplies.And also verified the Induction motor characteristics.

REFERENCES

[1] O. Garcia, J. A. Cobos, R. Prieto, P. Alou, and J. Uceda, "Single phasepower factor correction: A survey," IEEE Trans. Power Electron., vol. 18,no. 3, pp. 749–755, May 2003.

[2] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P.Kothari, "A review of single-phase improved power quality AC-DC converters," IEEE Trans. Ind. Electron., vol. 50, no. 5, pp. 962–981, Oct. 2003.

[3] M. M. Jovanovic and Y. Jang, "State-of-the-art, single-phase, active powerfactorcorrection techniques for high-power applications—An overview,"IEEE Trans. Ind. Electron., vol. 52, no. 3, pp. 701–708, Jun. 2005.

[4] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications, and Design. Hoboken, NJ, USA: Wiley, Oct. 2002.

[5] T. Yan, J. Xu, F. Zhang, J. Sha, and Z. Dong, "Variable-on-time-controlledcritical-conduction-mode flyback PFC converter," IEEE Trans. Ind. Electron., vol. 61, no. 11, pp. 6091–6099, Nov. 2014.

[6] D. G. Lamar, M. Arias, A. Rodriguez, A. Fernandez, M. M. Hernando,and J. Sebastian, "Design-oriented analysis and performance evaluationof a low-cost high-brightness LED driver based on flyback power factorcorrector," IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2614–2626,Jul. 2013.

[7] C. Zhao, J. Zhang, and X. Wu, "An improved variable on-time controlstrategy for a CRM flyback PFC converter," IEEE Trans. Power Electron.,vol. 32, no. 2, pp. 915–919, Feb. 2017.

[8] J. W. Shin, S. J. Choi, and B. H. Cho, "High-efficiency bridgeless flybackrectifier with bidirectional switch and dual output windings," IEEE Trans.Power Electron., vol. 29, no. 9, pp. 4752–4762, Sep. 2014.

[9] C.-P. Tung and H. S.-H.Chung, "A flyback AC/DC converter using powersemiconductor filter for input power factor correction," in Proc. IEEE Appl.Power Electron. Conf. Expo., Long Beach, CA, USA, 2016, pp. 1807–1814.

[10] L. Gu, W. Liang, M. Praglin, S. Chakraborty, and J. M. Rivas Davila,"A wide-input-range high-efficiency step-down power factor correctionconverter using variable frequency multiplier technique," IEEE Trans.Power Electron., vol. 33, no. 11, pp. 9399–9411, Nov. 2018.

[11] K. Mino et al., "Novel bridgeless PFC converters with low inrush currentstress and high efficiency," in Proc. Int. Power Electron. Conf.—ECCEASIA, Sapporo, Japan, 2010, pp. 1733–1739.

[12] M. Alam, W. Eberle, and N. Dohmeier, "An inrush limited, surge toleranthybrid resonant bridgeless PWM AC-DC PFC converter," in Proc. IEEEEnergy Convers. Congr.Expo., Pittsburgh, PA, USA, 2014, pp. 5647–5651.

[13] A. H. Memon, K. Yao, Q. Chen, J. Guo, and W. Hu, "Variable-on-timecontrol to achieve high input power factor for a CRM-integrated buckflyback PFC converter," IEEE Trans. Power Electron., vol. 32, no. 7,pp. 5312–5322, Jul. 2017.

[14] H. S. Athab, D. Dah-Chuan Lu, A. Yazdani, and B. Wu, "An efficientsingle-switch quasi-active PFC converter with continuous input currentand low DC-bus voltage stress," IEEE Trans. Ind Electron., vol. 61, no. 4,pp. 1735–1749, Apr. 2014.

[15] S. W. Lee and H. L. Do, "A single-switch AC-DC LED driver based on aboost-flyback PFC converter with lossless snubber," IEEE Trans. PowerElectron., vol. 32, no. 2, pp. 1375–1384, Feb. 2017.

[16] J. I. Baek, J. K. Kim, J. B. Lee, H. S. Youn, and G. W. Moon, "A boostPFC stage utilized as half-bridge converter for high-efficiency DC-DCstage in power supply unit," IEEE Trans. Power Electron., vol. 32, no. 10,pp. 7449–7457, Oct. 2017.

[17] M. A. Bakar and K. Bertilsson, “An improved modelling and constructionof power transformer for controlled leakage inductance,” in Proc. IEEE16th Int. Conf. Environ.Elect. Eng., Florence, Italy, 2016, pp. 1–5.
[18] R. Mitova, R. Ghosh, U. Mhaskar, D. Klikic, M. X. Wang, and A. Dentella,“Investigations of 600-V GaN HEMT and GaN diode for power converterapplications,” IEEE Trans. Power Electron., vol. 29, no. 5, pp. 2441–2452,May 2014.
[19] A. M. Abou-Alfotouh, A. V. Radun, H. R. Chang, and C. Winterhalter,“A 1-MHz hard-switched silicon carbide DC/DC converter,” IEEE Trans.Power Electron., vol. 21, no. 4, pp. 880–889, Jul. 2006.
[20] J. S. Glaser et al., “Direct comparison of silicon and silicon carbide powertransistors in high-frequency hard-switched applications,” in Proc. 26thAnnu. IEEE Appl. Power Electron. Conf. Expo., Fort Worth, TX, USA,2011, pp. 1049–1056.
[21] H. Wu, Y. Lu, T. Mu, and Y. Xing, “A family of soft-switching DC-DCconverters based on a phase-shift-controlled active boost rectifier,” IEEETrans. Power Electron., vol. 30, no. 2, pp. 657–667, Feb. 2015.
[22] C. A. Quinn and D. B. Dalal, “Empowering the electronics industry: Apower technology roadmap,” CPSS Trans. Power Electron. Appl., vol. 2,no. 4, pp. 306–319, Dec. 2017