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High Frequency Transformer Designing For Flyback And Forward Converter

Mr. Devendra P. Jumade[1], Mr. Nikhil Wadokar[2]
[1] HOD, Electronics & Telecommunication Engineering Dept., Vikramshila Polytechnic, Darapur, Amravati, Maharashtra, India.
[2] Asst. Professor, Electrical Power System Engineering Dept., Dr. Sau. Kamaltai Gawai Institute of Engineering and Techonology, Darapur, Amravati, Maharashtra, India.

Abstract
For flyback and forward converters, the transformer is the most important factor that determines the performance such as the efficiency, output regulation and electromagnetic induction (EMI). Contrary to the normal transformer, the flyback transformer is inherently an inductor that provides energy storage, coupling and isolation for the flyback converter. In the general transformer, the current flows in both the primary and secondary winding at the same time. However, in the flyback transformer, the current flows only in the primary winding while the energy in the core is charged and in the secondary winding while the energy in the core is discharged. Usually gap is introduced between the core to increase the energy storage capacity.
This paper presents practical design considerations of high frequency transformers for flyback and forward converters employing High Frequency Transformer (HFT). In order to give insight to the reader, practical design examples are also provided.
Key Words: Electromagnetic Induction (EMI), High Frequency Transformer (HFT)

I. GENERAL TRANSFORMER DESIGN PROCEDURE 1

1.1 Choose The Proper Core 1

Core Type : Ferrite is the most widely used core material for commercial SMPS (Switchied mode power supply) applications. Various ferrite cores and bobbins are shown in Fig -1. The type of the core should be chosen with regard to system requirements including number of outputs, physical height, cost and so on. Table 1 shows features and typical application of various cores.

Fig -1 : Ferrite Core (TDK)

Core	**Feature**	**Typical Application**
EEEI	-Low Cost	Auxiliary Power Battery Charger
EFD EPC	-Low Profile	LCD Monitor
EER	-Large Winding Window Area _Various Bobbins for Multiple Output	CRT Monitor, C-TV, DVDP, STB
PQ	-Large Cross Sectional Area -Relatively Expensive	

Table -1 : Features and typical applications of various cores

Core size: Actually, the initial selection of the core is bound to be crude since there are too many variables. One way to select the proper core is to refer to the manufacture's core selection guide. If there is no proper reference, use the Table-2 as a starting point. The core recommended in Table-1 is typical for the universal input range, 67kHz switching frequency and 12V single output application. When the input voltage range is 195-265 Vac (European input range) or the switching frequency is higher than 67kHz, a smaller core can be used. For an application with low voltage and/or multiple outputs, usually a larger core should be used than recommended in the table.

Output Power	EI Core	EE Core	EPC Core	EER Core
0-10W	EI12.5 EI16 EI19	EE8 EE10 EE13 EE16	EPC10 EPC13 EPC17	
10-20W	EI22	EE19	EPC19	EER25.5
20-30W	EI25	EE22	EPC25	EER28
30-50W	EI28 EI30	EE25	EPC30	EER28L
50-70W	EI35	EE30		EER35
70-100W	EI40	EE35		EER40
100-150W	EI50	EE40		EER42
150-200W	EI60	EE50 EE60		EER49

Table -2 : Core quick selection table (For universal input range, fs=67kHz and 12V single output)

Once the core type and size are determined, the following variables are obtained from the core data sheet.
- Ae : The cross-sectional area of the core (mm2)
- Aw : Winding window area (mm2)
- Bsat : Core saturation flux density (tesla)

II. HIGH FREQUENCY TRANSFORMER DESIGN FOR FLYBACK AND FORWARD CONVERTER MODES 2

2.1 The Flyback Converter

Fig-2 shows the basic circuit diagram of a Flyback converter. Its main parts are the transformer, the primary switching MOSFET Q1, secondary rectifier D1, output capacitor C1 and the PWM controller IC. Depending on the design of T1, the Flyback can operate either in CCM (Continuous Conduction Mode) or DCM (Discontinuous Conduction Mode). In DCM, all the energy stored in the core is delivered to the secondary during the turn off phase (Flyback period), and the primary current falls back to zero before the Q1 switch turns on again. For CCM, the energy stored in the transformer is not completely transferred to the secondary; that is, the Flyback current (ILPK and ISEC) does not reach zero before the next switching cycle.

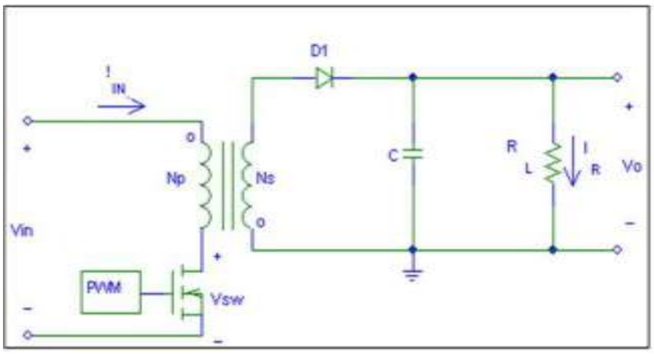

Fig -2 : Flyback Converter Schematic

Fig-3 shows the difference between CCM and DCM mode in terms of Flyback primary and secondary current waveforms

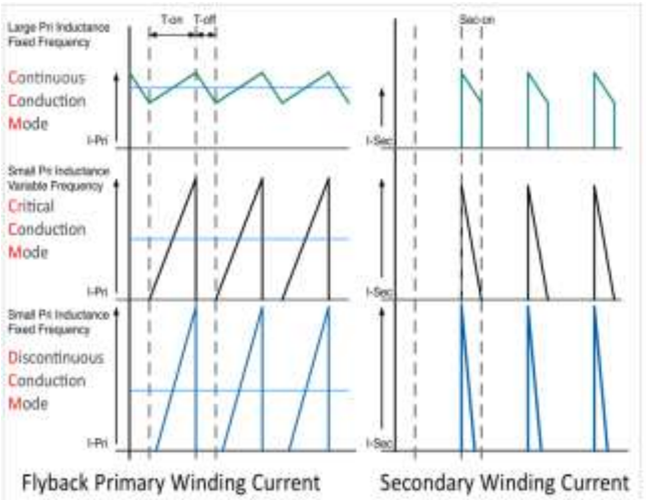

Fig -3 : Flyback Curent Waveform

Fig-2 shows the basic topology of a fly-back circuit. Input to the circuit may be unregulated dc voltage derived from the utility ac supply after rectification and some filtering. The ripple in dc voltage waveform is generally of low frequency and the overall ripple voltage waveform repeats at twice the ac mains frequency. Since the SMPS circuit is operated at much higher frequency (in the range of 100 kHz) the input voltage, in spite of being unregulated, may be considered to have a constant magnitude during any high frequency cycle. A fast switching device ('S'), like a MOSFET, is used with fast dynamic control over switch duty ratio (ratio of ON time to switching time-period) to maintain the desired output voltage. The transformer, in Fig.-2, is used for voltage isolation as well as for better matching between input and output voltage and current requirements. Primary and secondary windings of the transformer are wound to have good coupling so that they are linked by nearly same magnetic flux. As will be shown in the next section the primary and secondary windings of the fly-back transformer don't carry current simultaneously and in this sense fly-back transformer works differently from a normal transformer. In a normal transformer, under load, primary and secondary windings conduct simultaneously such that the ampere turns of primary winding is nearly balanced by the opposing ampere-turns of the secondary winding (the small difference in ampere-turns is required to establish flux in the non-ideal core). Since primary and secondary windings of the fly-back transformer don't conduct simultaneously they are more like two magnetically coupled inductors and it may be more appropriate to call the fly-back transformer as inductor-transformer. Accordingly the magnetic circuit design of a fly-back transformer is done like that for an inductor. The details of the inductor-transformer design are dealt with separately in some later lesson. The output section of the fly-back transformer, which consists of voltage rectification and filtering, is considerably simpler than in most other switched mode power supply circuits. As can be seen from the circuit (Fig-2), the secondary winding voltage is rectified and filtered using just a diode and a capacitor. Voltage across this filter capacitor is the SMPS output voltage.

It may be noted here that the circuit shown in Fig-2 is rather schematic in nature. A more practical circuit will have provisions for output voltage and current feedback and a controller for modulating the duty ratio of the switch. It is quite common to have multiple secondary windings for generating multiple isolated voltages. One of the secondary outputs may be dedicated for estimating the load voltage as well as for supplying the control power to the circuit. Further, as will be discussed later, a snubber circuit will be required to dissipate the energy stored in the leakage inductance of the primary winding when switch 'S' is turned off. Under this section, for ease of understanding, some simplifying assumptions are made. The magnetic circuit is assumed to be linear and coupling between primary and secondary windings is assumed to be ideal. Thus the circuit operation is explained without consideration of winding leakage inductances. ON state voltage drops of switches and diodes are neglected. The windings, the transformer core, capacitors etc. are assumed loss-less. The input dc supply is also assumed to be ripple-free.

2.2 Derivation of The Flyback Converter

The flyback converter is based on the buck-boost converter. Its derivation is illustrated in Fig-4. Fig-4(a) depicts the basic buck-boost converter, with the switch realized using a MOSFET and diode. In Fig-4(b), the inductor winding is constructed using two wires, with a 1:1 turns ratio. The basic function of the inductor is unchanged, and the parallel windings are equivalent to a single winding constructed of larger wire. In Fig-4(c), the connections between the two windings are broken. One winding is used while the transistor Q1 conducts, while the other winding is used when diode D1 conducts.

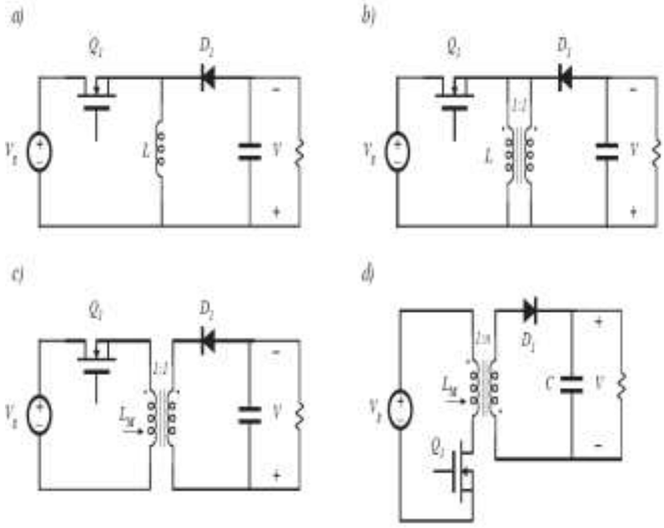

Fig -4 : Derivation of The Flyback Converter:
(a) Buck-Boost Converter,
(b) Inductor L is wound with two parallel wires,
(c) Inductor windings are isolated, leading to the flyback converter,
(d) With a 1:n turns ratio and positive output.

The total current in the two windings is unchanged from the circuit of Fig-4(b); however, the current is now distributed between the windings differently. The magnetic fields inside the inductor in both cases are identical. Although the two-winding magnetic device is represented using the same symbol as the transformer, a more descriptive name is "twowinding inductor". This device is sometimes also called a "flyback transformer". Unlike the ideal transformer, current does not flow simultaneously in both windings of the flyback transformer. Fig-4(d) illustrates the usual configuration of the flyback converter. The MOSFET source is connected to the primary-side ground, simplifying the gate drive circuit. The transformer polarity marks are reversed, to obtain a positive output voltage. A 1: n turns ratio is introduced; this allows better converter optimization.

2.3 A Practical Fly-Back Converter

The fly-back converter discussed in the previous sections neglects some of the practical aspects of the circuit. The simplified and idealized circuit considered above essentially conveys the basic idea behind the converter.

However a practical converter will have device voltage drops and losses, the transformer shown will also have some losses. The coupling between the primary and secondary windings will not be ideal. The loss part of the circuit is to be kept in mind while designing for rated power. The designed input power (Pin) should be equal to Po/η, where Po is the required output power and η is the efficiency of the circuit. A typical figure for η may be taken close to 0.6 for first design iteration. Similarly one needs to counter the effects of the non-ideal coupling between the windings. Due to the non-ideal coupling between the primary and secondary windings when the primary side switch is turned-off some energy is trapped in the leakage inductance of the winding. The flux associated with the primary winding leakage inductance will not link the secondary winding and hence the energy associated with the leakage flux needs to be dissipated in an external circuit (known as snubber). Unless this energy finds a path, there will be a large voltage spike across the windings which may destroy the circuit.

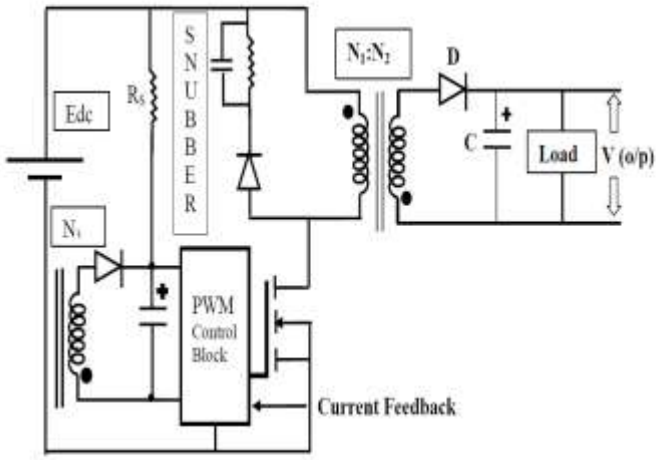

Fig -5 : A Practical Fly Back Converter

Fig-5 shows a practical fly-back converter. The snubber circuit consists of a fast recovery diode in series with a parallel combination of a snubber capacitor and a resistor. The leakage-inductance current of the primary winding finds a low impedance path through the snubber diode to the snubber capacitor. It can be seen that the diode end of the snubber capacitor will be at higher potential. To check the excessive voltage build up across the snubber capacitor a resistor is put across it. Under steady state this resistor is meant to dissipate the leakage flux energy. The power lost in the snubber circuit reduces the overall efficiency of the fly-back type SMPS circuit. A typical figure for efficiency of a fly-back circuit is around 65% to 75%. In order that snubber capacitor does not take away any portion of energy stored in the mutual flux of the windings, the minimum steady state snubber capacitor voltage should be greater than the reflected secondary voltage on the primary side. This can be achieved by proper choice of the snubber-resistor and by keeping the RC time constant of the snubber circuit significantly higher than the switching time period. Since the snubber capacitor voltage is kept higher than the reflected secondary voltage, the worst-case switch voltage stress will be the sum of input voltage and the peak magnitude of the snubber capacitor voltage. The circuit in Fig-5 also shows, in block diagram, a Pulse Width Modulation (PWM) control circuit to control the duty ratio of the switch. In practical fly-back circuits, for closed loop output voltage regulation, one needs to feed output voltage magnitude to the PWM controller. In order to maintain ohmic isolation between the output voltage and the input switching circuit the output voltage signal needs to be isolated before feeding back. A popular way of feeding the isolated voltage information is to use a tertiary winding. The tertiary winding voltage is rectified in a way similar to the rectification done for the secondary winding. The rectified tertiary voltage will be nearly proportional to the secondary voltage multiplied by the turns-ratio between the windings. The rectified tertiary winding voltage also doubles up as control power supply for the PWM controller. For initial powering up of the circuit the control power is drawn directly from the input supply through a resistor (shown as RS in Fig-5) connected between the input supply and the capacitor of the tertiary circuit rectifier. The resistor 'RS' is of high magnitude and causes only small continuous power loss.

In case, multiple isolated output voltages are required, the fly-back transformer will need to have multiple secondary windings. Each of these secondary winding voltages are rectified and filtered separately. Each rectifier and filter circuit uses the simple diode and capacitor as shown earlier for a single secondary winding. In the practical circuit shown above, where a tertiary winding is used for voltage feedback, it may not be possible to compensate exactly for the secondary winding resistance drop as the tertiary winding is unaware of the actual load supplied by the secondary winding. However for most applications the small voltage drop in the winding resistance may be tolerable. Else, one needs to improve the voltage regulation by adding a linear regulator stage in tandem or by giving a direct output voltage feedback to the control circuit.

2.4 The Forward Converter

Forward converter is another popular switched mode power supply (SMPS) circuit that is used for producing isolated and controlled dc voltage from the unregulated dc input supply. As in the case of fly-back converter (lesson-22) the input dc supply is often derived after rectifying (and little filtering) of the utility ac voltage. The forward converter, when compared with the fly-back circuit, is generally more energy efficient and is used for applications requiring little higher power output (in the range of 100 watts to 200 watts). However the circuit topology, especially the output filtering circuit is not as simple as in the fly-back converter.

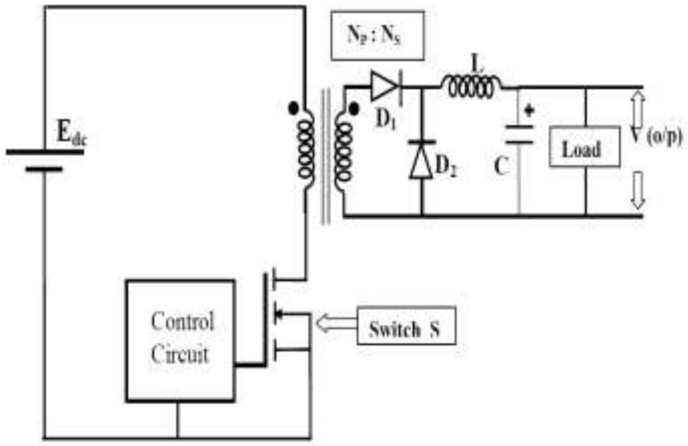

Fig -6 : Forward Converter Schematic

Fig-6 shows the basic topology of the forward converter. It consists of a fast switching device 'S' along with its control circuitry, a transformer with its primary winding connected in series with switch 'S' to the input supply and a rectification and filtering circuit for the transformer secondary winding. The load is connected across the rectified output of the transformer-secondary. The transformer used in the forward converter is desired to be an ideal transformer with no leakage fluxes, zero magnetizing current and no losses. The basic operation of the circuit is explained here assuming ideal circuit elements and later the non-ideal characteristics of the devices are taken care of by suitable modification in the circuit design. In fact, due to the presence of finite magnetizing current in a practical transformer, a tertiary winding needs to be introduced in the transformer and the circuit topology changes slightly. A more practical type forward converter circuit is discussed in later sections.

2.5 Derivation of The Forward Converter

The circuit of Fig-6 is basically a dc-to-dc buck converter with the addition of a transformer for output voltage isolation and scaling. When switch 'S' is turned on, input dc gets applied to the primary winding and simultaneously a scaled voltage appears across the transformer secondary.

Dotted sides of both the windings are now having positive polarity. Diode 'D1', connected in series with the secondary winding gets forward biased and the scaled input voltage is applied to the low pass filter circuit preceding the load. The primary winding current enters through its dotted end while the secondary current comes out of the dotted side and their magnitudes are inversely proportional to their turns-ratio. Thus, as per the assumption of an ideal transformer, the net magnetizing ampere-turns of the transformer is zero and there is no energy stored in the transformer core. When switch 'S' is turned off, the primary as well as the secondary winding currents are suddenly brought down to zero. Current through the filter inductor and the load continues without any abrupt change. Diode 'D2' provides the freewheeling path for this current. The required emf to maintain continuity in filter-inductor current and to maintain the forward bias voltage across D2 comes from the filter inductor 'L' itself. During freewheeling the filter inductor current will be decaying as it flows against the output voltage (Vop), but the presence of relatively large filter capacitor 'C' still maintains the output voltage

nearly constant. The ripple in the output voltage must be within the acceptable limits. The supply switching frequency is generally kept sufficiently high such that the next turn-on of the switch takes place before the filter inductor current decays significantly. Needless to say, that the magnitudes of filter inductor and capacitor are to be chosen appropriately.
The idea behind keeping filter inductor current nearly constant is to relieve the output capacitor from supplying large ripple current. [As per the circuit topology of Fig.23.1, the inductor and the capacitor together share the load-current drawn from the output. Under steady state condition, mean dc current supplied by the capacitor is zero but capacitor still supplies ripple current. For maintaining constant load current, the inductor and capacitor current-ripples must be equal in magnitude but opposite in sense. Capacitors with higher ripple current rating are required to have much less equivalent series resistor (ESR) and equivalent series inductor (ESL) and as such they are bulkier and costlier. Also, the ESR and ESL of a practical capacitor causes ripple in its dc output voltage due to flow of ripple current through these series impedances. Since the output voltage is drawn from capacitor terminal the ripple in output voltage will be less if the capacitor is made to carry less ripple current.]

2.6 A Practical Fly-Back Converter

Fig-7 shows the circuit topology of a practical forward converter. It takes into account the non-ideal nature of a practical transformer. Other non-idealities of the circuit elements like that of switch, diodes, inductor and capacitor are taken care of by modifying the circuit parameters chosen on the basis of ideal circuit assumption. Most common consequence of non-ideal nature of circuit elements is increase in looses and hence reduction in efficiency of the power supply. A practical way to get around the consequence of circuit losses is to over-design the power supply. The design should aim to achieve an output power of oPη, where 'oP' is the required output power and 'η' is the efficiency of the converter. As a first order approximation, a typical efficiency figure of around 80% may be assumed for the forward converter. Once the efficiency figure has been considered the circuit may still be designed based on the simplified analysis presented here, which neglects many of the non-idealities. Another common non-ideality is the low frequency ripple and fluctuation in input dc supply voltage. In the simplified analysis input supply has been assumed to be of constant magnitude. In a practical circuit, the variation in input supply is taken care of by modulating the switch duty ratio in such a manner that it offsets the effect of supply voltage fluctuation and continues to give the required quality of output voltage.

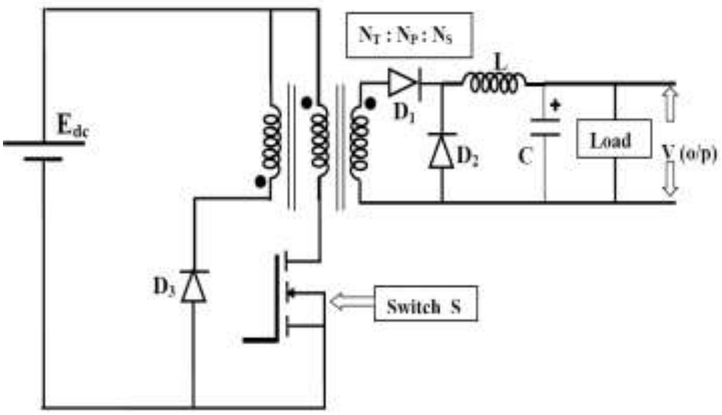

Fig -7 : A Practical Forward Converter

The non-ideality of the transformer, however, cannot simply be overcome by changing the circuit parameters of the simplified circuit shown in Fig-7. A practical transformer will have finite magnetization current and finite energy associated with this magnetization current. Similarly there will be some leakage inductance of the windings. However, windings of the forward-converter transformer will have much smaller leakage inductances than those of fly-back converter transformer. In fly-back transformer's flux path some air-gap is deliberately introduced by creating a gap in the transformer core. Introduction of air gap in the mutual flux path increases the magnitude of leakage inductances. Transformer of a forward converter should have no air-gap in its flux path. The forward-converter transformer works like a normal power transformer where both primary and secondary windings conduct simultaneously with opposing magneto motive force (mmf) along the mutual flux path. The difference of the mmfs is responsible for maintaining the magnetizing flux in the core. When primary winding current is interrupted by switching off 'S', the dotted ends of the windings develop negative potential to oppose the interruption of current (in accordance with Lenz's law). Negative potential of the dotted end of secondary winding makes diode 'D1' reverse biased and hence it also stops conducting. This results in simultaneous opening of both primary and secondary windings of the transformer. In case the basic circuit of Fig-7 is used along with a practical transformer, turning off of switch 'S' will result in sudden demagnetization of the core from its previously magnetized state. Each time the switch 'S' is turned off the snubber circuit will dissipate the energy associated with the magnetizing flux. This, as has been seen in connection with fly-back converter, reduces the power-supply efficiency considerably. A more preferred solution is to recover this energy. For this reason the practical forward converter uses an extra tertiary winding with a series diode, as shown in Fig-7. When both switch 'S' and 'D1' turn-off together, as discussed above, the magnetization energy will cause a current flow through the closely coupled tertiary winding and the diode 'D3'. The dot markings on the windings are to be observed. Current entering the dot through any of the magnetically coupled windings will produce magnetic flux in the same sense. As soon as switch 'S' is turned off, the dotted end voltages of the windings will become negative in accordance with Lenz's law. The sudden rise in magnitude of negative potential across the windings is checked only by the conduction of current through the tertiary winding. As discussed earlier unless the continuity in transformer flux is maintained the voltages in the windings will theoretically reach infinite value. Thus turning off of switch 'S' and turn-on of diode 'D3' need to be simultaneous. Similarly fall in magnetizing current through primary winding must be coupled with simultaneous rise of magnetization current through the tertiary winding. In order that the entire flux linking the primary winding gets transferred to the tertiary, the magnetic coupling between these two windings must be very good. For this the primary and tertiary winding turns are wound together, known as bifilar windings. The wires used for bifilar windings of the primary and the tertiary need to withstand large electrical voltage stress and are costlier than ordinary transformer wires.

III. CONCLUSIONS

Thus the required high frequency transformer designing for flyback and forward converter achieves output voltage will be obtained by giving low dc energy source such as 12V input to the circuit. Later the given voltage will be boosted up by the forward and fly back converter. The boosted up voltage will then filtered from harmonics by using filter. The performance of the proposed converter was verified on a 150-kHz, 450-W prototype circuit that was designed to operate from a universal ac-line input. The generated voltage is ready to Supply the load. With Transformer ratio we can vary the output voltage to reach maximum and we can takes a multiple value output.

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