Implementation of a Primary Tapped Transformer in a High Frequency Isolated Power Converter

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***Abstract*—On load, transformer primary tap changing is not common in high frequency converters. This paper investigates a new converter topology to drive primary tapped transformers. The ideas that have been introduced previously are simply implemented into existing converter topologies which have been modified to accommodate a primary tapped transformer. The effects of efficiency with variation of source voltage and duty cycle are studied. It is shown that this topology can maintain a load voltage for a much wider source voltage variation without major sacrifices in efficiency.**

Keywords-High frequency; primary tapped transformer; power converters; variable voltage source.

I. INTRODUCTION

Secondary tapped transformers are commonly used in high frequency power converters to provide various isolated output voltages. These taps normally sit on the secondary and are used to provide various output voltages. The output voltages of secondary tapped transformers need to be individually regulated in order to obtain the desired output voltage per tap. The output voltage of each secondary tap will have a minimum and maximum limit due to variations in source voltage and duty cycle control.

Primary tapped transformers have rarely been considered for implementation in high frequency isolated power converters. Ideas of primary tapped transformer topologies have been proposed in [1], but are simply modifications of existing topologies. These ideas show that by implementing primary taps, the source voltage can be varied to a much larger extent and maintain a relatively good efficiency for a constant output voltage.

Primary tapped transformers are often used in low frequency applications to regulate output voltages as proposed in [2]. These low frequency tapped transformers are capable of changing taps on load at sub-transmission and distribution levels.

Problems have been identified with tap changing power supplies in [3], where SCR's were used to change primary taps of low frequency power supplies. Problems occurred with the sudden change of the taps with the SCR's. Methods of improving these problems for tap changers under load have been investigated in [4]. The switching of these taps is relatively slow, but methods have been devised to speed up the tap switch capability as was done in [5] where IGBT's, instead of SCR's are used as the tap switch.

These low frequency taps can be changed under load conditions with programmable logic controllers as described in [6]. The controllers have become more complex and have allowed tap changing transformers to be implemented into multi-level converters to improve the quality of an AC sine waveform as was done in [7].

Voltage regulation in power electronic converters is normally done using duty cycle control. This method of control has proven to be effective, but has its drawbacks since different converter topologies have better efficiencies at certain duty cycles. Most converters are less efficient at low duty cycles. For a large variation in source voltage, a second or third power supply is required, if the output voltage cannot be sustained due to a limitation in the duty cycle.

Power electronic converters are also normally designed to operate at a specific source voltage with little variance and have high efficiencies at the designed source voltage.

For a varying source voltage, the efficiency is sacrificed and the output voltage might not be sustained due to the duty cycle range. The combined effects of duty cycle limitations and variation in source voltage are factors that need to be addressed for future converter topologies.

Low frequency power systems implement primary taps to regulate the output voltage if there is a variation in the source voltage. This idea can be extended to isolated power converter topologies by implementing tapped transformers or coupled inductors on the primary side as the proposed ideas in [1]. By adding winding taps to the primary, the efficiency can be kept steadier for a greater variation of source voltage.

A new isolated converter strategy for primary tapped transformers is discussed in this paper extending the ideas of [1]. It is shown that primary tapped transformers can support a wide operating source voltage range, but unlike the ideas in [1], this paper introduces a high frequency under load primary tap changing transformer scheme.

The ideas addressed, are aimed at solving the problems of source voltage variation and the output voltage regulation with the limitation of duty cycle, while maintaining a relatively constant efficiency. The isolated topology investigated is characterized using a varying source voltage. The results are recorded and presented in this paper.

II. THREE CONVERTER VARIABLE VOLTAGE SOURCE POWER SUPPLY

Before the primary tapped transformer converter idea is introduced, it must be compared to a similar converter with similar capability. Thus a low power, power supply was devised using three separate converters in order to obtain the same expected results so that they may be compared.

A. Topology Overview

This initial converter prototype was built on breadboard to investigate the effects of three different transformer ratios and yield results to which the final design can be compared to.

The topology presented resembles three separate power supplies powered from the same source and share the same controller and voltage source but have independent drivers.

The three transformers were chosen to have a step-up (1:2), one-to-one (2:2) and step up (3:2) winding ratios. The reason for these transformer winding ratios shall be revealed when the new topology is discussed. The control strategy of this test prototype has been simplified and is indicated in Fig. 1.

The load voltage as well as the source voltage is measured by the controller. The controller then decides on the relevant transformer to be switched and at what duty cycle to obtain the desired output voltage.

The topology of this three transformer converter is shown in Fig. 2. The three different transformers are indicated as T1, T2 and T3. Each of the transformers secondary outputs is rectified and then connected in parallel to the load.

Each of the 12 switches (S1 – S12) requires an anti-parallel diode for free-wheeling, but these have been left out in the schematic diagram.

The converter was built on breadboard and thus has inherent stray inductance which reduces the maximum power capability of the circuit.

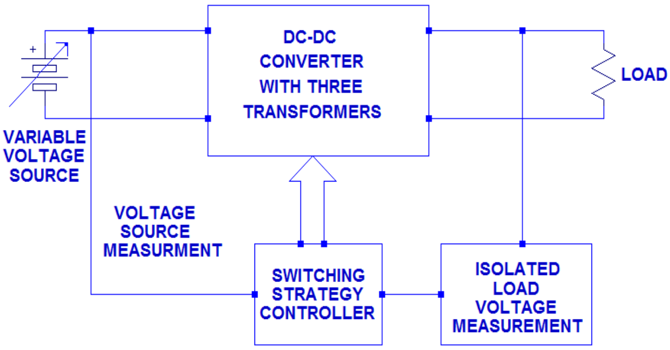

Figure 1. Block diagram for three separate transformers

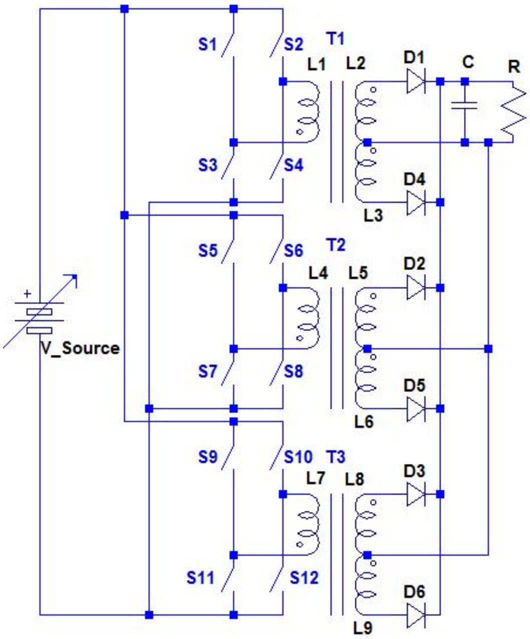

Figure 2. Three transformer circuit constructed to investigate possibility of primary tapped transformers and effects

B. Experimental Results

The converter that was built on breadboard is indicated in Fig. 3 where the three separate transformers are clearly seen.

For each if the transformers, the source voltage is varied and the duty cycle adjusted (5%-45%) in order to keep the output voltage constant to 15V DC. The input power and output power is also measured each time and the power efficiency calculated for each measurement.

The results have been plotted in an intelligible manner such that they can be compared to the results of the primary tapped transformer which is discussed later. The power efficiency vs. duty cycle plot for the initial experimental setup is shown in Fig. 4.

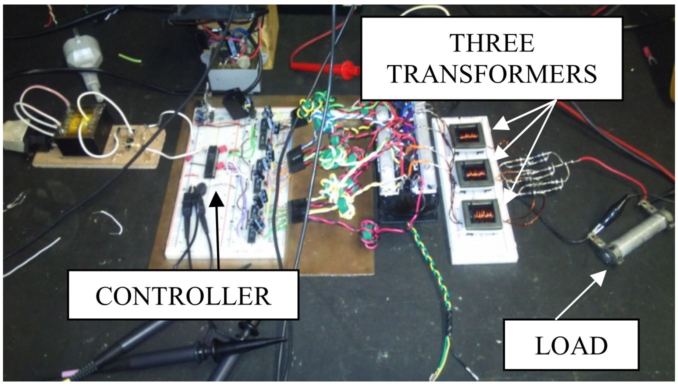

Figure 3. Initial circuit idea constructed on breadboard

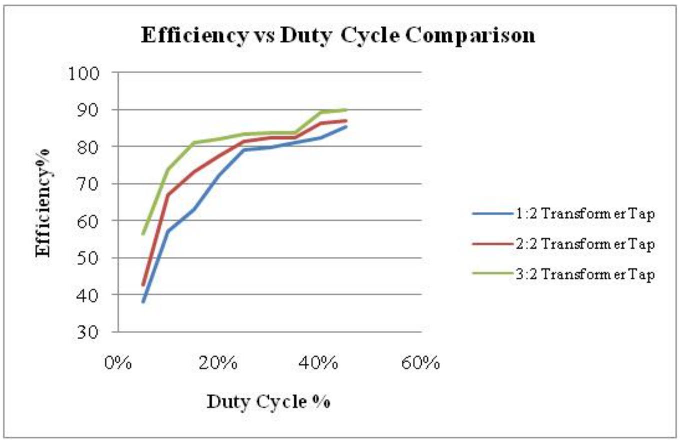

Figure 4. Efficiency vs. duty cycle plot for initial experimental setup

Fig. 4 clearly indicates that the efficiency, whilst maintaining a constant output power, is extremely low at lower duty cycles, and at higher duty cycles, the efficiency is considerably better. These characteristics were observed for each of the transformers. The 3:2 transformer efficiency performed better overall. This is because less current is drawn from the source hence the switching losses are relatively low.

Keeping these results in mind, the converters efficiency vs. source voltage plot was obtained and is shown in Fig. 5. It can be seen that each transformer can only sustain the desired output voltage for a limited variance in source voltage. The source voltage variance is different for each transformer, with some overlap.

This is useful since each tap performs better for different source voltages. This is used to determine when to change taps. The optimum source voltage for when to change taps is indicated by the vertical lines added to Fig. 5.

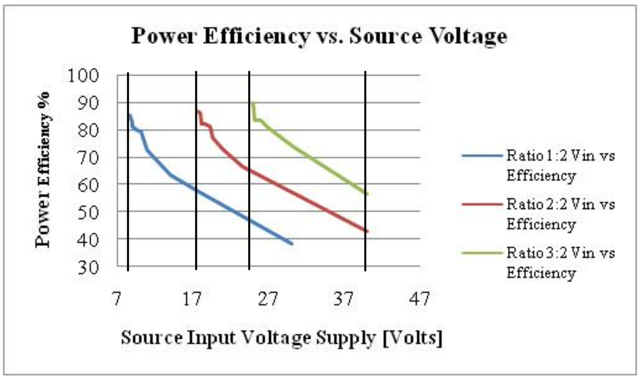

Figure 5. Power efficiency vs. source voltage for each tap.

If we choose a minimum efficiency of 55% for this converter, then the source voltage variance extends from $9V_{DC}$ all the way to $40V_{DC}$. Individually, the transformers cannot obtain this source voltage variance. Although using the transformers characteristics intelligently and by switching the taps at $18V_{DC}$ and again at $25V_{DC}$, the source voltage may be varied to a much wider extent without sacrificing the efficiency of the converter.

These results form a baseline to which the primary tapped transformer topology can be compared. It should be noted that the switch count for this test converter is quite high. Using three different transformers is also not feasible. The aim is to reduce magnetic components and reduce the number of switches and still yield similar results. Thus the next step investigates the integration of the transformers into a single core and reducing the switch count.

III. NOVEL CONVERTER WITH PRIMARY TAPPED TRANSFORMER

The work done is further extended with the investigation of a primary tapped, high frequency transformer which accommodates 3 different winding ratios on a single core and reduces the switch count.

A. Topology Overview

In order to maintain consistency in the measurements, similar components were used for the new converter design. The operating concept of the primary tapped transformer topology can be seen in the block diagram shown in Fig. 6. This is a similar concept to the converter discussed earlier, the difference being the switch arrangement and using a single transformer instead of three separate cores.

To maintain the isolation between the tapped primary and the secondary of the transformer, the load voltage measurement is isolated.

The source voltage is also measured and fed to the controller. The controller then uses these measured quantities to decide which transformer ratio and what duty cycle to use that will yield the optimum converter efficiency and maintain the output voltage.

The general switch layout is shown in Fig. 7. This topology achieves three different transformer ratios with just two primary windings by modulating the relevant switches within these three phase arms similar to an H-bridge.

When compared to the idea in Figure 1, it is clear that the switch count has been reduced from 12 switches down to 8 with the topology proposed in this paper. The number of drivers required also reduces since there are fewer switches required for this three phase arm topology.

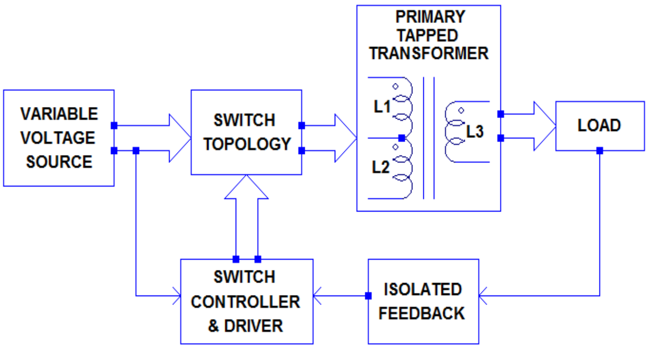

Figure 6. Block diagram of converter topology

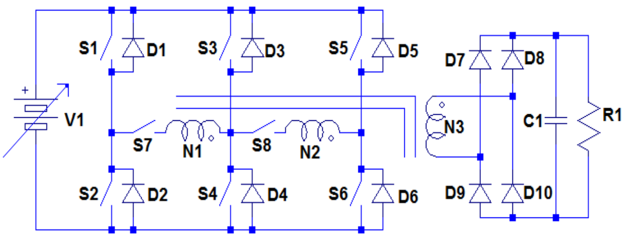

Figure 7. General switch layout

Winding ratios of 1:2 (N1:N3), 2:2 (N2:N3) and 3:2 (N1+N2:N3) were chosen because these give the three options of step-up, one-one and step-down. Unlike the converter discussed earlier which has three separate cores, these windings all sit on a single core of the same size as the previous transformers.

When one set of primary windings is energized, the other primary will also induce a voltage. This induced voltage will cause short circuit conditions due to the free-wheeling diodes in the remainder of the circuit. This can be solved by simply adding two extra switches namely S7 and S8. These are accompanied with four external diodes allowing them to become bi-directional switches as shown in Fig. 8(a). The anti-parallel diode of the switche has been ignored for clarity.

The high frequency bi-directional switch idea is presented in [5] where it was used for faster response on a tapped transformer application which can change tap on load. The fast response of the bi-directional switch allows it to easily break a conduction path. Since the conduction path is broken, no current will be allowed to flow thus allowing the winding ratio to be controlled through the primary taps without the problem of the induced voltage causing short circuit currents.

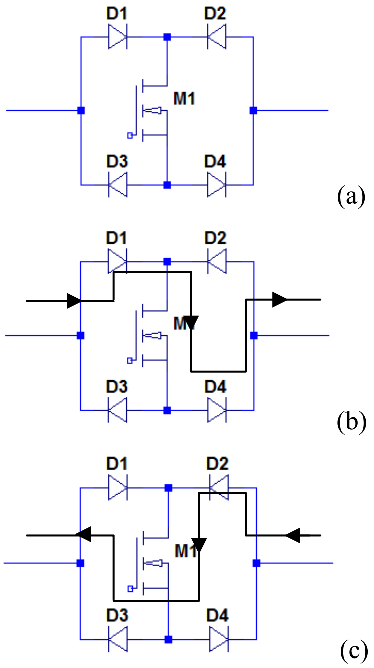

Figure 8. High frequency bi-directional switch

Fig. 8(b) and Fig. 8(c) indicates how the diode-switch configuration can conduct in both directions when the switch is on. When the switch is off, the current path is removed and blocks the current from both directions.

The basic schematic of the switch layout for this new switching scheme with three phase arms is simplified slightly as shown in Fig. 9. To explain the switching concept using the three phase arms, the free-wheeling diodes have been left out in the schematic diagram. The primary windings individually form a 1:2 and 2:2 winding ratio with the secondary, but when operated in series yield a third winding ratio of 3:2 with the secondary. This is better understood by analyzing the switching scheme as presented in Fig. 9 and Table I.

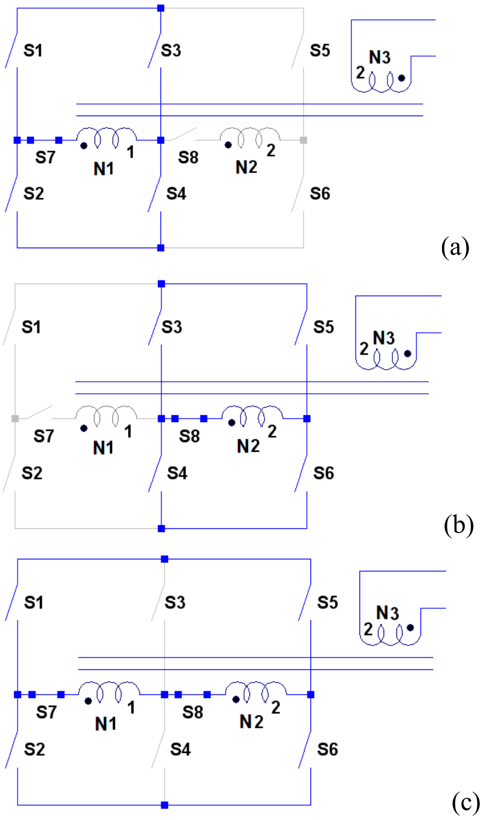

Figure 9. Intelligent primary tapped transformer switching technique

TABLE I. LOGIC OPERATION OF PRIMARY TAPPED TRANSFORMER TOPOLOGY SUMMARY

Desired Operation	**Modulated Switches**						**Tap Selection Switches**		**Winding Ratio**
	S1	***S2***	***S3***	***S4***	***S5***	***S6***	***S7***	***S8***	
Step-Up (Fig.9(a))	1	1	1	1	0	0	1	0	N1:N3 1:2
One to One (Fig.9(b))	0	0	1	1	1	1	0	1	N2:N3 2:2
Step-Down (Fig.9(c))	1	1	0	0	1	1	1	1	N1+N2:N3 3:2

This intelligent switching scheme and the tapped primary transformer converter topology explained above, can maintain a constant output power for a wide variation of source voltage.

The efficiency can also be maximized similar to the scheme where 3 different converters are used.

B. Experimental Results

In order to prove and investigate the operating concept of this three phase arm primary tapped transformer topology, a low power prototype was again constructed.

The prototype constructed for experimental confirmation can be seen in Fig. 10. The transformer windings were interleaved to reduce the leakage inductance and improve the coupling. The same experimental procedure was conducted as before, using a variable DC source voltage. The source voltage was varied for each of the winding ratios and the duty-cycle adjusted (5%-45%) to keep the output voltage constant ($15V_{DC}$).

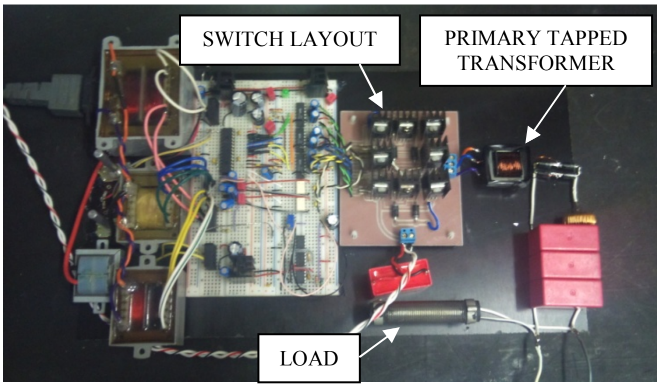

Figure 10. Bread-board circuit of topology with transformer.

The efficiency vs. duty cycle plot is shown in Fig. 11. This indicates that at low duty cycles the converter efficiency is low and at high duty cycles the efficiency is considerably better.

In comparison to the results obtained previously in Fig.4, the overall efficiency is slightly lower; otherwise there is little difference in the results. This minor reduction in efficiency is believed to be due to an increased proximity losses in the primary tapped transformer.

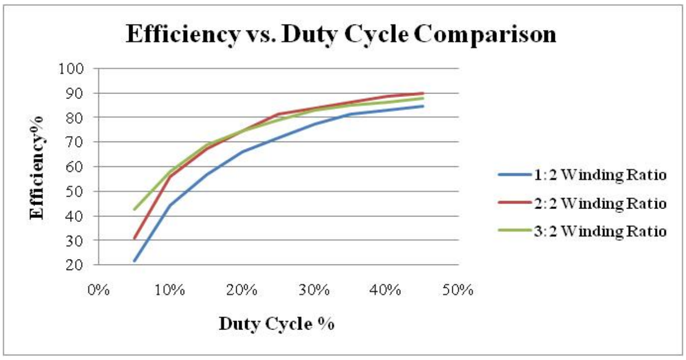

Figure 11. Efficiency vs. duty cycle plot for the primary tapped transformer converter topology idea

The power efficiency for the three phase arm primary tapped transformer can also be analyzed. The optimum source voltage to determine when to switch winding ratios (or taps) is presented by noting the power efficiency vs. source voltage while adjusting the duty cycle to maintain s constant output power. These results are indicated in Fig. 12.

The source voltage range is limited for any one of the winding ratios, but the three different ratios cover a much wider range (with overlap) which allows for considerably more variance in the source voltage. These same characteristics are seen in the previous converter design with three separate transformers. The efficiency is also kept higher using this converter by switching to the relevant winding ratio.

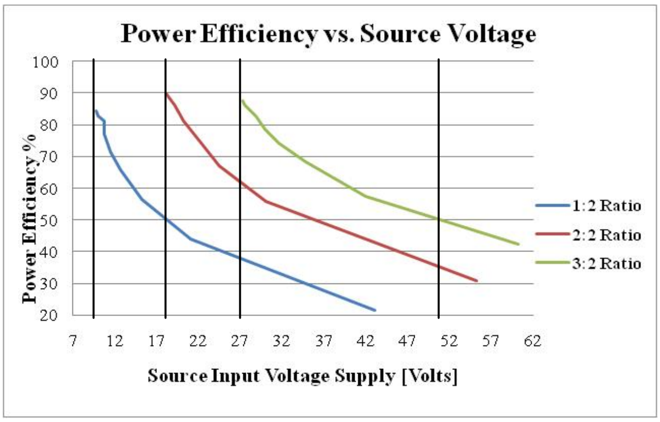

Figure 12. Intelligent primary tapped transformer switching technique

If the converter is chosen to operate with a minimum power efficiency of 50%, then the source voltage ranges from a minimum of $9V_{DC}$ all the way to $51V_{DC}$. This can only happen if the correct winding ratio is selected according to the ranges indicated by the vertical lines added to Fig. 12.

Having obtained these results, they can now be compared to those obtained earlier with the converter with three separate transformers.

The three-phase-arm converter design uses fewer components than the previous converter and achieves comparable results making it a more viable option for a power supply which is subject to a wide variation in the source voltage.

IV. FUTURE WORK

These results clearly prove the concept of using primary tapped transformers and the switch topology with reduced switch count. Such converters can become extremely versatile in many environments where the winding ratio would have to be changed under load operating conditions.

Much work still has to be done where the converter is fed from an AC supply and the impact on power factor should be determined.

V. CONCLUSION

The concept of implementing tapped primary transformers in high frequency DC-DC converters has successfully been illustrated. A wide source voltage variation can be accommodated by simply switching to the corresponding winding ratio that will yield the maximum efficiency. The output voltage can be regulated easily with the closed loop feedback implemented into the system.

Further research is presently being done to observe the power factor of this topology and switching strategy when fed from AC supplies.

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