# Evaluation Of a Novel Primary Tapped Transformer In a High Frequency Isolated Power Converter Topology

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***Abstract*—The concept of primary tapped transformers is new in high frequency power electronic converters. This paper evaluates a new converter topology which has been developed to implement a high frequency primary tapped transformer. It is shown that this topology can maintain a load voltage for a much wider source voltage variation without major sacrifices in efficiency. The effect of efficiency with variation of source voltage and duty cycle as well as the power quality of the converter is analyzed experimentally. This new topology is evaluated in terms of complexity, capability, feasibility and reliability. The power quality aspects are also addressed. Possible end users of such a topology design are also taken into consideration.**

***Index Terms*—High frequency converter, primary tapped transformer, variable voltage source, converter topology.**

## I. Introduction

On-load primary tapped transformers are commonly used for voltage regulation of low frequency power system applications as shown in [1] and [2]. On-load primary tapped transformers are not common in high frequency converters. High frequency power electronic converters often implement transformers not only for electrical power transformation, but also for isolation. The secondary or output voltage is varied by adjusting duty cycle. This adjustment of duty cycle can reach its limits for a wide variance in input voltage making it unable to sustain the correct output voltage through duty cycle control alone. The efficiency of the converter also changes as the duty cycle is varied. A novel topology has been proposed in [3], [4] and [5] to solve this problem for isolated converters.

This new topology is included in this paper for the convenience of the reader in Fig. 1. This paper shall evaluate the converter in terms of power quality among other aspects. The feasibility of the converter shall also be discussed. Possible uses of such a topology as well as possible applications, where this topology will not be well suited, shall also be discussed.

## II. Common problems with isolated converters:

Converters are often designed for specific applications. Different topologies have been optimized for use in different applications. The power quality and feasibility of the converter is often the deciding factor for the final solution, as well as the cost.

One of the key design parameters before deciding on a topology is to consider whether isolation is required. The topology considered in this paper is electrically isolated through a transformer. Isolation is important for power electronic converters to ensure that sudden changes in the system are not reflected throughout which can damage costly components and control systems.

Wide variance in source voltage is a common problem in renewable energy generators. This is a common issue with renewable resources as an alternative power source for electrical energy conversion. Continuously changing weather conditions will vary the available resource of energy such as solar panels and wind generators. This varies the generated voltage. The generated voltage needs to be regulated and stabilized in order to be synchronized to a grid with other electrical power sources. To accommodate this variance as well as having the ability to stabilize and regulate the voltage, power electronic converters are used as discussed in [6], [7], [8]. The topology evaluated in this paper can accommodate a wide variance in source voltage and still maintain a constant DC output voltage [9].

Topologies are constantly being modified, but the component count is a major cost factor for the application. Modifications can mean that extra components are required, thus increasing the overall cost. The topology discussed in [5] boasts that fewer components are required for this topology layout than for a similar converter which can achieve the same specifications. The topology evaluated in this paper was not optimized in [4] or [5]; the design was introduced and proven to operate experimentally, thus allowing the opportunity for further investigation.

The topology design is evaluated in this paper ensuring that it is in fact feasible and worthy for further investigation. A short explanation of the new three phase arm converter topology is discussed next for the convenience of the reader, followed by an evaluation thereof.

## III. New three phase arm converter topology used for switching a high frequency isolated converter

This new converter topology consists of three phase arms as indicated in Fig. 1. This converter is able to achieve three different winding ratios with only two primary windings.

Switches S7 and S8 are the key components that allow this converter to achieve this. The center switches S7 and S8 in series with the primary taps in Fig. 1 must be high frequency bi-directional switches. The reason for requiring these bi-directional switches is to prevent short circuit conditions via body diodes and is discussed further in [4].

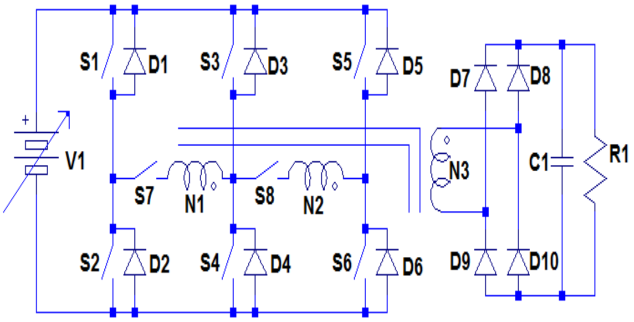


Fig. 1. Novel three phase arm topology for high frequency primary tapped transformers

A simple high frequency bi-directional switch can be made, as found in [10], by using four diodes and a standard MOSFET as shown in Fig. 2. A high side or isolated gate drive should be used for this bi-directional switch.

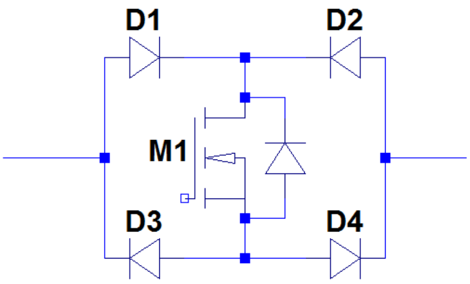


Fig. 2. High frequency bi-directional switch

## A. Operation of the new topology

The operation of this topology is best described with Fig. 3. To achieve the step up winding ratio, consider Fig. 3(a). Switches S5, S6 and S8 are to remain open circuit. S7 is to remain closed circuit and the remaining switches, S1, S2, S3 and S4 are modulated as a normal full bridge converter. This will activate N1 (and remove N2) and will act as a transformer with N3 with winding ratio of 1:2.

Consider Fig. 3(b), the one-to-one ratio is similarly achieved by keeping switches S1, S2 and S7 open circuit. S8 is to remain closed, switches S3, S4, S5 and S6 are then modulate in full bridge converter mode. This will activate N2 (and remove N1) and couple with N3 to form a winding ratio of 2:2.

Finally Fig. 3(c) shows that the step down ratio is achieved by keeping S3 and S4 open circuit and S7 and S8 closed. Then switches S1, S2, S5 and S6 form a full bridge converter which then forces N1 in series with N2 to couple with N3 which act as a transformer with winding ratio of 3:2 (N1+N2:N3).

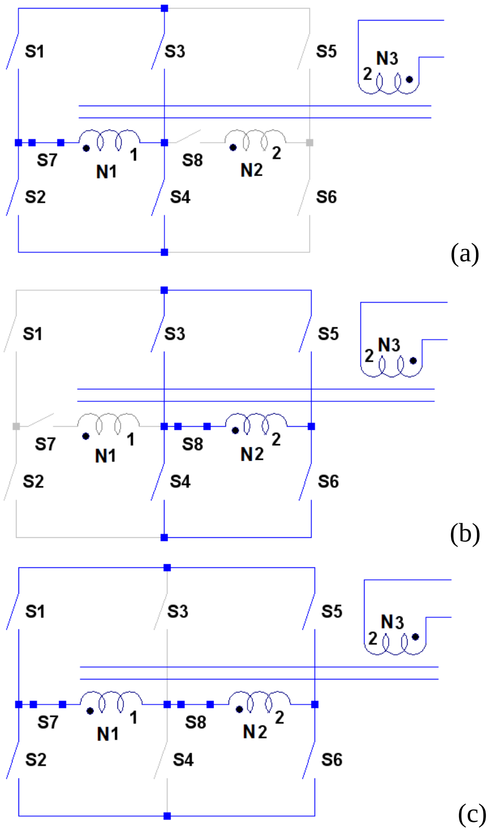


Fig. 3. Switching scheme for primary taps using three phase arm topology

The operation of the converter topology is summarized in Table I. The variable "D" in Table I is the duty cycle of the converter. The duty cycle is a maximum of 0.5 for this topology similar to a full bridge converter.

TABLE I: LOGIC TABLE DEMONSTRATING SWITCHING STAGES

| **Desired Operation** | **Modulated Switches** | | | | | | **Tap Selection Switches** | | **Transfer Function** |
|---|---|---|---|---|---|---|---|---|---|
| | ***S1*** | ***S2*** | ***S3*** | ***S4*** | ***S5*** | ***S6*** | ***S7*** | ***S8*** | |
| **Step-Up** Fig. 3(a) **N1:N3** 1:2 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | $\frac{V_{OUT}}{V_{IN}} = 2D\frac{N1}{N3}$ |
| **One to One** Fig. 3(b) **N2:N3** 2:2 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | $\frac{V_{OUT}}{V_{IN}} = 2D\frac{N2}{N3}$ |
| **Step-Down** Fig. 3(c) **N1+N2:N3** 3:2 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | $\frac{V_{OUT}}{V_{IN}} = 2D\frac{N1+N2}{N3}$ |

This switching method can easily be automated with a microcontroller. The control is more complex than that of a normal full-bridge converter in the way that more switches need to be controlled simultaneously. The switch count is however lower than the case where separate full bridges were used to switch separate transformer primaries as discussed in [5].

## IV. EVALUATION OF THE NOVEL PRIMARY TAPPED TRANSFORMER IN A HIGH FREQUENCY ISOLATED POWER CONVERTER

The operation of the novel three phase arm converter has been explained. The converter is now evaluated while considering the operation aspects of the converter.

### *A. Evaluation for DC source voltage:*

The ability for the converter to maintain a constant DC output voltage is considered next. The results obtained from [9] are shown in Fig. 4.

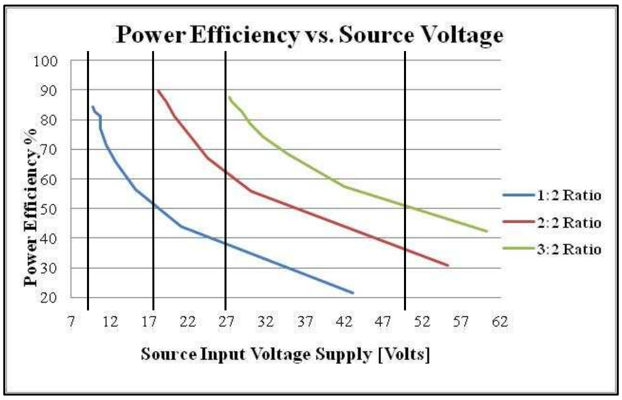


Fig. 4. Electrical power efficiency plotted against a varied source voltage

The results of Fig. 4 indicate that this converter is able to maintain a constant output voltage for a wide variance in source voltage without dropping below efficiency of 50%. A better explanation of Fig. 4 and Fig. 5 can be found in [4]. The topology was not optimized for any specific operation. The design can possibly be optimized for specific operating regions, making it well suited for specific applications.

As with most converter topologies, when operated at low duty cycles, the efficiency is decreased. This is no different for this topology as can be seen with Fig. 5. At low duty cycles, the efficiency of the converter is low. This occurs at all of the tap change possibilities. As expected with the step-up winding ratio, the converter efficiency is lower for all duty cycles. This is because the higher current flows through the primary winding and switches, hence the losses in the switches increase.

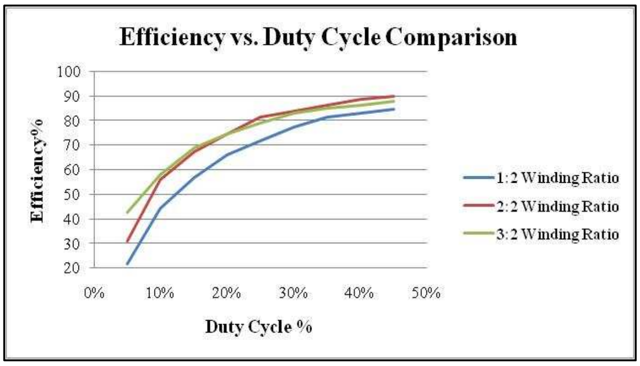


Fig. 5. Electrical power efficiency plotted against a varied duty cycle

#### *1) Efficiency:*

A relatively high efficiency can be maintained with this topology. The prototype that was experimented with in [5] was a low power design. With some optimization of the design, this topology can be implemented into high power converter applications.

Similar to any power electronic topology, the type of power switches used can be changed to any sort of power switching device, depending on the application and the desired switching frequency. The switching devices require an anti-parallel diode for free-wheeling currents.

The high frequency bi-directional switch inherently has two diode volt drops per half cycle when under operation. This will contribute a great deal to the overall losses of the converter. This bi-directional switch should be replaced with a more efficient bi-directional switch, or low volt drop diodes should be used to minimize the losses in that relevant current path. This can limit the maximum power capability of the converter, because higher current flowing through these diodes means that the diodes themselves will also require a heat sink.

#### *2) Output voltage stability:*

The output voltage can be maintained for a wide variance in source voltage. There are still upper and lower voltage limits to which a specified output voltage can be maintained. A converter can be designed to accommodate the same source voltage limits and still maintain the output voltage, but the efficiency will be sacrificed. This aspect makes this primary tapped converter topology more attractive for high power conversion.

The converter setup was only tested with a predominantly resistive load. The effects of inductive or capacitive loading were not investigated.

#### *3) Complexity of converter:*

The complexity of a converter may determine its usefulness and feasibility. Complex converters often have complex problems and these problems can take longer to solve, causing longer downtime. Thus a simpler converter is often chosen for power conversion in industry.

The control of this converter is similar to that of a full bridge converter. The main complexity of the control is synchronizing the additional switches. Additional complexity that is introduced is the voltage sensing and more specifically, when to switch between primary taps. This is indicated with the vertical lines added in Fig. 4. The feedback is similar to most measurement setups for the control of power electronic converters. The complexity of a converter requires highly skilled personnel.

#### *4) Cost of converter:*

The key limiting factor when designing a converter is the cost. The components that contribute greatly to the overall cost are:

- Power semiconductors and rectifiers
- DC bus capacitors
- Magnetic component
- Microcontroller

- Heat sink

A total of 8 semi-conductor switches are required for this converter topology. In order to make a cost comparison, this topology must be compared to a converter or power supply which can achieve the same operation. This has been done in [3] and [4] where it was shown that this three phase arm topology requires fewer switches when compared to a power supply which can achieve the same operation. This will have a relative reduction in the cost of such a topology. It should be noted that although fewer switches are required, the number of rectifiers depends on the type of rectification chosen.

Heat sink cost depends on the efficiency and allowable operating temperature. Since this converter is able to operate at a higher efficiency range, this could imply less heat sink material is required. Although, the correct selection of semi-conductor switches and gate drivers will play a large role in the required heat sink size as well.

In [4] and [9] it was experimentally shown and proven that this converter topology requires less overall DC bus capacitance when powered from a rectified AC voltage source as discussed in the next section. Less required bus capacitance can imply a reduction in the cost as well as the size of the converter.

A primary tapped transformer requires multiple primary windings, implying that for the same power rating, a larger magnetic core will be required to fit the extra windings. The cost of the main magnetic component will increase because of the extra copper that must be accommodated. A larger magnetic core has the advantage of not being able to saturate easily, but its disadvantage is that the leakage inductance, losses as well as the magnetizing current are more than that of a smaller core.

The chosen microcontroller will have to be more complex and will thus cost more. The microcontroller can also be used for any auxiliary circuitry that might want to be added. In which case having a single more complex micro can possibly be beneficial.

*5) Robustness:*

The circuit can only be as robust as the design, although the fewer the components, the less that can go wrong. If the circuit is designed well and the components are overrated for their specification, the converter will be robust. It should be noted that this topology is able to operate at a relatively high efficiency. Hence less strain will be placed on the switching semi-conductors which could increase their expected lifespan.

This possible increased lifespan can make this topology more reliable for certain applications where the converter offers critical voltages that need to be maintained.

### *B. Evaluation for rectified AC source voltage:*

The three phase arm converter can also be fed with a rectified AC voltage source as explained in detail in [4]. The rectified waveform can be fed directly to the converter and no DC bus capacitance is required on the input. DC bus capacitance is only required on the output. Less overall DC bus capacitance is required for this converter setup.

The source voltage waveform is sinusoidal, but the source current is not. The source current changes because of the tap change between the primary taps of the transformer to regulate the output voltage. Between certain voltage levels different primary tap winding ratios are used to regulate the output voltage. This tap change causes a sudden change in source current is shown in Fig. 6.

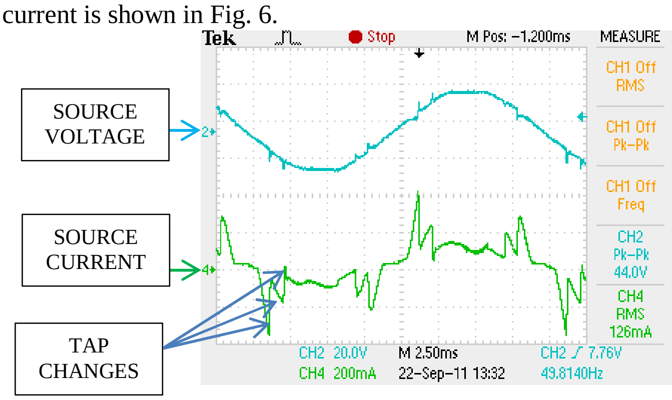


Fig. 6. Source voltage and current waveforms of the three phase arm converter when powered from a rectified AC source voltage

The power quality of the converter will be similar to that of any full bridge DC-DC converter if it is fed from a DC voltage source because of its similar operation. The power quality of the converter when fed from a rectified AC voltage source is a different matter and must be evaluated.

*1) Power quality*

The power quality of this converter to this present moment has not been evaluated other than in [9]. The definitions used are in accordance with the IEEE 1459 standard [11]. Power quality aspects which are analyzed in this paper are only those of fundamental power factor, total power factor and total harmonic distortion of the current. The voltage is assumed to be fairly sinusoidal and any THD is assumed negligible compared to that of the current.

Power quality is an important specification of any power converter. In order to fairly analyze the power quality of the three phase arm converter, it will be measured against a standard rectifier and capacitor setup commonly used as the input stage of AC-DC converters. This common setup is normally what causes the main non-linearity, in the current waveform as shown in Fig. 6, which decreases the power factor and power quality.

The power quality is determined by analyzing the source power, namely the voltage and the current. The source voltage and source current waveforms for one period are indicated in Fig. 6. The fundamental power factor, ($PF_1$), is expected to be close to unity because the converter operation forces the current to be drawn from the source closely in phase with the voltage. The source current waveform seems to be in phase with the voltage waveform.

It is clear from the time domain representation of the current waveform of Fig. 6 that the current waveform contains harmonics. This will decrease the power quality of the converter. The harmonics are introduced during the tap change between the primary windings. Since the winding ratio changes at every tap change, the current drawn from the source is also forced to change. This disruption in the source current is represented by the peaks in the current waveform in the time domain.

The power quality and the total harmonic distortion were measured using three methods in [9]. The first power measurement was done using numerical analysis on the captured waveforms. A Discrete Fourier Transform (DFT) was also used to numerically determine the fundamental power factor. The captured waveform was then exported into MATLAB SIMULINK powergui toolbox where the Total Harmonic Distortion (THD) and the power factor were determined. An Erich Marek power meter was used. The Erich Marek is a fairly old instrument, but is known to be quite accurate because of its thermal measurement method of measuring power. The next set of results was obtained with a Fluke 41B power harmonic analyzer. This device digitizes the signal and then determines the fundamental power factor, the THD and the total power factor.

The final measurement instrument used to determine the power quality was a Yokogawa 2533 digital power meter. The Yokogawa also digitizes the measured signals and determines the power factor. The results are expected to vary because of the difference as well as the tolerance of the transducers within the measurement instruments used. The results are indicated in Table II. In order to analyze the results and make useful conclusions, the results for the new converter are compared to a standard rectifier and capacitor setup found on the input stage of most power electronic converters. The same AC voltage source was used for all experimental setups; this was done in order to maintain consistency for the different measurements.

Firstly the ideal case is indicated in Table II. The ideal scenario is when there is no phase difference between the source voltage and current, and both are sinusoidal. The AC voltage source was then loaded with the rectifier and capacitor setup as discussed above. This setup was loaded so that the same RMS current drawn from the source is similar to that which is drawn from the three phase arm converter. This was done in order to create a setup to which the power quality can be compared.

The results in Table II clearly indicate that the fundamental power factor of the three phase arm converter is closer to unity than the rectifier and capacitor setup. The results for the power factor show inconclusive results. This is because the power factor results obtained do not indicate any conclusive result in the total power factor. This would not have been noticed if only one measurement instrument was used to determine the power quality. The bandwidth limitations of each instrument need to be taken into consideration. The voltage and current measurement transducer tolerances of each instrument will also cause the variance in the measured results.

Regardless of the exactness of the measurements, it is clear that this converter and its topology hold useful potential. With more attention and optimization of the design, the converter can be useful.

TABLE II: POWER QUALITY MEASUREMENTS OF THE THREE PHASE ARM CONVERTER TOPOLOGY

| **Method** | **Numerical Analysis** | | | **Fluke 41B** | | | **Erich Marek** | **YOKO-GAWA** |
|---|---|---|---|---|---|---|---|---|
| ***Setup*** | $PF_1$ ***(DFT)*** | $THD_I$ | $PF$ | $PF_1$ | $THD_I$ | $PF$ | $PF$ | $PF$ |
| ***Ideal*** | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| ***Rectifier and Capacitor*** | 0.82 | 88.5% | 0.6 | 0.85 | 74% | 0.7 | 0.74 | 0.73 |
| ***New Converter*** | 0.962 | 109% | 0.7 | 0.902 | 58% | 0.8 | 0.723 | 0.642 |

*2) EMI:*

Under DC source voltage conditions, the THD is the same as that of any other switching converter and common EMI filters can be used. When powered from a rectified AC source voltage, the converter introduces harmonics in the source current. This high concentration of harmonics will generate EMI. This high EMI is unwanted in any power electronic device. A comparison of the amount of THD of different common converters can be found in [12]. It is shown that these common converters can be adapted to perform power factor correction. This three phase arm converter unfortunately will cause harmonics because of its operating method. The magnitude of these harmonics can be reduced by optimizing the design.

This EMI generation will be common to both this three phase arm topology as well as the topology to which it is compared in [4]. The operating principle of adjusting taps consecutively and repeatedly is the root cause of this EMI. The concept of primary tapped transformers is interesting, but requires more research before it is feasible for commercial applications. The EMI of the topology can be reduced and the power factor improved with future work on the topology.

## V. CONCLUSION

It is difficult to properly evaluate such a converter. This is because there are no other primary tapped high frequency converter topologies to which this converter can be compared. High frequency primary tapped transformers in isolated power converters are not common in power electronic converters. Thus to evaluate the design, one can merely criticize and identify the negative aspects, and possibly the improvements required.

This three phase arm converter is well suited when used as a DC-DC converter. The results indicate that this converter performs well and is able to maintain a constant DC output voltage with little variance in efficiency for a wide variance in source voltage. Thus a possible application for such a converter is for renewable energy. The continuously varying generated power can be stabilized using this converter design. Smaller installations of renewable energy resources (solar or wind generators on boats for example) can use this converter as a voltage and power regulator and stabilizer.

This power supply works well when supplied from a DC input voltage or for wide but slow-varying DC voltages. Any large step changes in the source voltage will result in harmonics generated at that step. The switching transitions between the different primary taps generate harmonics. This generated a lot of EMI and reduced the power quality of the converter.

When the converter is fed from an AC source, the power quality is not good. This is because of the continuous switching of current drawn from the source. The power quality as well as the power factor of this converter must be improved if it is to be fed with a rectified AC voltage source. Although the overall required DC bus capacitance is effectively reduced, the converter has a bad power quality, as with any other similar converter.

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 closed loop feedback implemented into the system.

Further research is presently being done into the possibility of using this topology and switching strategy to improve the power quality of these converters when fed from AC supplies. This implies reducing the THD of the converter. Ways of adapting this topology for potential use as a power factor correction front end converter are also presently being investigated.

The converter is still new and requires modifications, expansions and experimentation before it becomes a mature and reliable topology. This converter has potential and should be investigated further.

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