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Topology, Analysis and Switching Strategy of Single Phase Electronic Transformer

Hitendrasinh C. Chawda
Lect. In Electrical Engg. Dept. of Electrical Engineering, R.C.T.I. Sola, Ahmedabad, Gujarat.

ABSTRACT
Transformers are widely used in electrical power utilization, distribution and power conversion systems to perform many functions, such as isolation, voltage transformation, noise decoupling, etc. Transformers are one of the most bulky and expensive parts in a power distribution and power conversion systems. The size of transformer is a function of saturation flux density of the core material and maximum allowable core and winding temperature rise. Saturation flux density is inversely proportional to frequency and increasing the frequency allows higher utilization of the steel magnetic core and reduction in transformer size. The subject of a high frequency link has been studied extensively in power electronic systems.In this paper electronic transformer is introduced. The advantages of the proposal are stated, topology, analysis and switching strategy of single phase Electronic Transformer are discussed. The primary purpose is to reduce the size and weight and volume and to improve efficiency.

KEYWORDS : Electronic Transformer, IUT, topology, Analysis

I. Development of Intelligent Universal Transformer

The IUT assembly layout is shown as block diagram in Fig.1. The layout is based on solid state transformer. It requires two power conversion stages: rectifying stage and inverting stage.

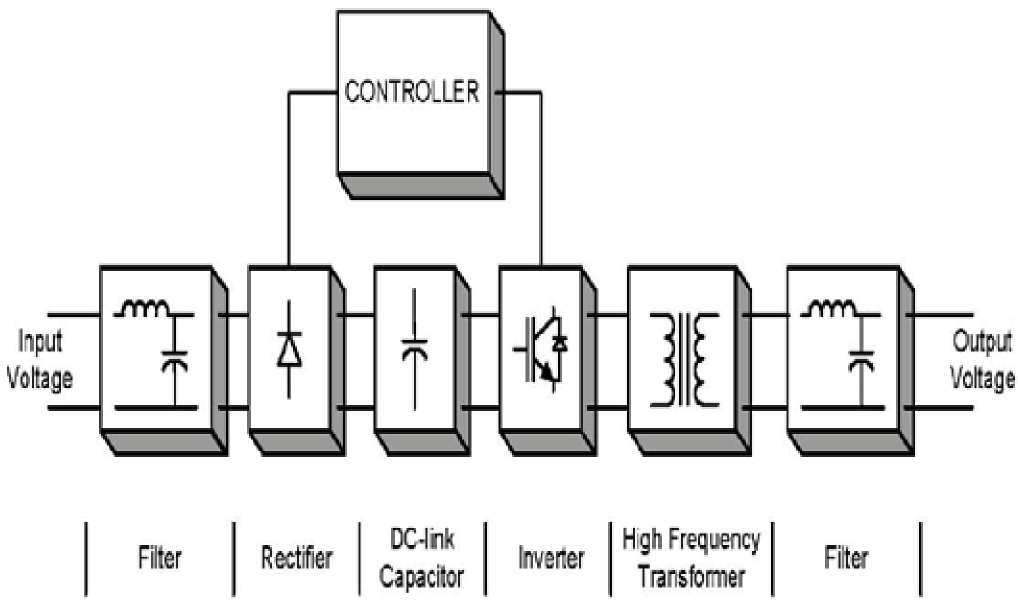


Fig. 1 EPRI intelligent universal transformer (IUT) layout.

The advantages of the IUT over conventional distribution transformer are:

1. Improved power quality.

2. DC and alternative frequency AC service options.
3. Integration with system monitoring, advanced distribution automation and open communication architecture.
4. Reduced weight and size.
5. Elimination of hazardous liquid dielectrics.
6. Reduced spare inventories.

Some drawbacks of the approach can be stated as followed:

1. Multiple power conversion stages can lower the transformer efficiency.
2. DC-link capacitors are required.
3. The transformer lifetime is shorter due to storage devices.

II. High frequency transformer

A transformer can be designed in small size by operating transformer core at high frequency. The high frequency transformer shows significantly different characteristics from the low frequency transformer. Core selection requires relationship between available output power and transformer parameters, such as core area product, peak flux density, operating frequency, and coil current density. Operating magnetic core at high frequency causes increase in core and copper losses.

III. Electronic transformer system

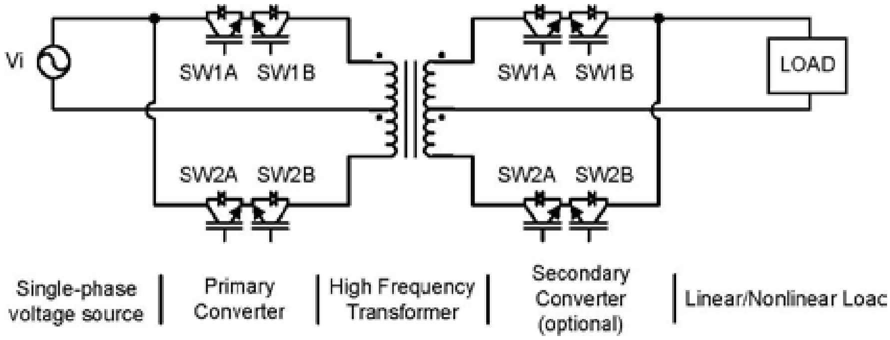
Electronictransformer with concept of a high frequency AC link is introduced in [1]. The electronic transformer system consists of static AC/AC power converters applying to primary and/or secondary windings of the transformer. Each converter contains bi-directional switches, which provide bi-directional energy flow. The low frequency (60/50 Hz) input voltage is converted to desired high operating frequency voltage through the primary converter, then the secondary converter restores the original low frequency input voltage. The secondary converter is optional. It is needed when the transformer supplies linear load type, and the operation requires both primary and secondary side static converters to operate synchronously. The subject of high frequency AC link has been studied widely in power electronic systems.

The electronic transformer has advantages as followed:

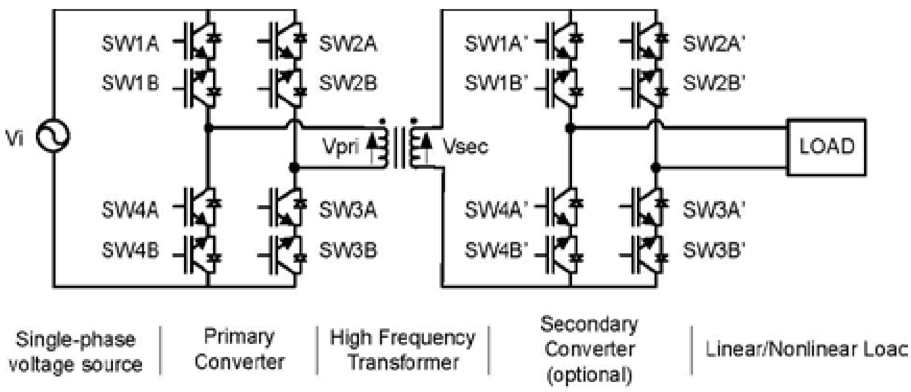
1. Identical input and output characteristic as a conventional transformer.
2. Efficiency compatible with a conventional transformer.
3. Snubber-less operation through 4-step switching strategy.
4. No additional harmonics generated due to switching.
5. Significantly smaller size and weight than a conventional transformer.

IV. Topology of electronic transformer

Topologies of single phase electronic transformer system are shown in Fig.2. Single phase AC/AC converters are applied to primary and secondary windings of a transformer.



(a) Half-bridge single phase electronic transformer system.



(b) Full-bridge single phase electronic transformer system.

Fig. 2 Topologies of single phase electronic transformer system.

Fig.2(a) shows the topology of single phase electronic transformer system, which includes AC/AC converters with bi-directional switches connecting in half-bridge arrangement. Fig.2(b) shows the topology of single phase electronic transformer system, which includes AC/AC converters with bi-directional switches connecting in full-bridge arrangement. The topology in Fig.2(a) requires the least number of bi-directional switches, but larger size of transformer than the topology shown in Fig.2(b).

V. Analysis of Single phase electronic transformer system

The single phase electronic transformer system shown in Fig. 2 (b) is analyzed mathematically as followed. Considering linear load condition, V_i is input voltage, and I_L is load current.

$V_i = V_m \sin \omega_i t$............(1)

$I_L = I_m \sin(\omega_i t - \emptyset)$......(2)

where

V_m is peak input voltage.

I_m *is* peak *load current.*

ω_i is angular input frequency.

∅ is power factor angle.

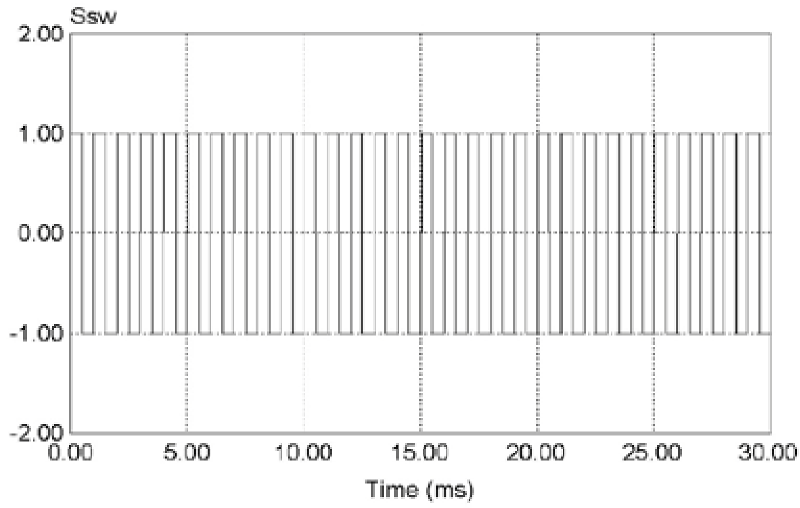


Fig. 3. Switching function for single phase electronic transformer system.

Switching function, S_{SW}, with 50% duty cycle as shown in Fig.3. It is expressed in Fourier series with switching angular frequency of ω_s in (3).

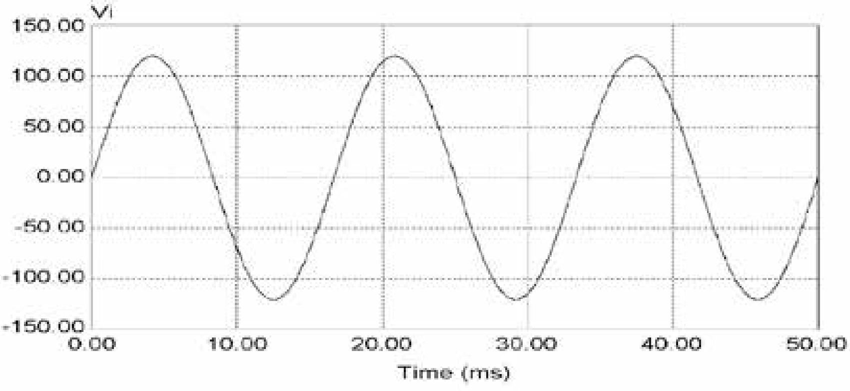
$$S_{sw} = \sum_{n=odd}^{\propto} \frac{4}{n\pi} \sin(n\omega_s t) \ldots\ldots(3)$$

The primary voltage of the transformer, V_{pri}, is the product of input voltage and the switching function as shown in (4). And the transformer primary winding current, I_{pri}, is the product of the load current and switching function as shown in (5).

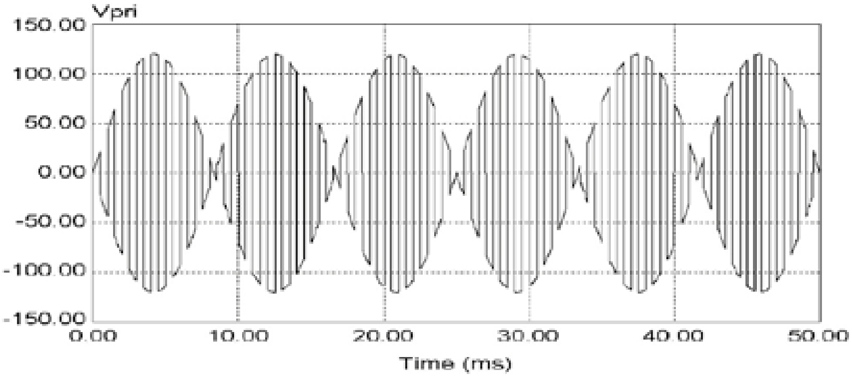
$$V_{pri} = V_i.S_{sw} = \frac{2V_m}{\pi} \sum_{n=odd}^{\propto} \frac{1}{n} [\cos(n\omega_s - \omega_i)t - \cos(n\omega_s + \omega_i)t] \ldots\ldots(4)$$

$$I_{pri} = I_i.S_{sw} = \frac{2I_m}{\pi} \sum_{n=odd}^{\propto} \frac{1}{n} [\cos((n\omega_s - \omega_i)t + \emptyset) - \cos((n\omega_s + \omega_i)t - \emptyset)] \ldots(5)$$

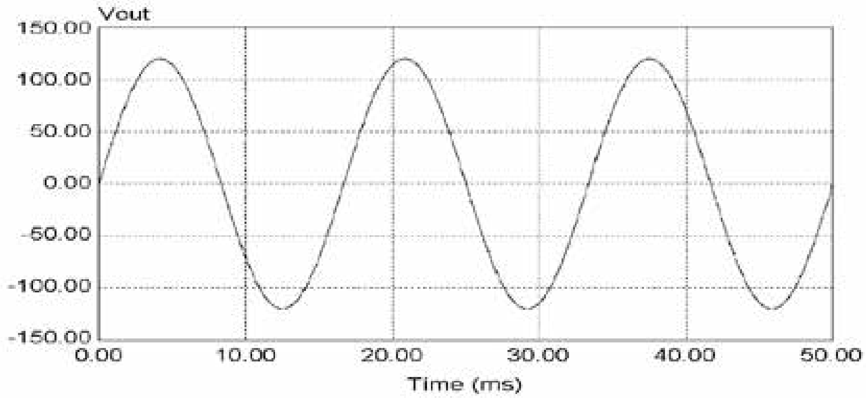
Fig.4 shows input voltage, transformer primary high frequency voltage, and output voltage of the single phase electronic transformer system in Fig.2(b).



(a) Input voltage V_i (120 V 60 Hz).



(b) Transformer primary voltage V_{pri} (1000 Hz).



(c) Output voltage V_{out},(120 V 60 Hz).

Fig.4. Single phase electronic transformer system voltages.

At nonlinear load condition, high frequency harmonic components of load current have effect to the current flowing through the transformer winding. Let the load current I_L be expressed in Fourier series as (6).

$I_L = \sum_{h=1}^{\propto} A_h \sin h\omega_i t)]$…(6)

The transformer winding current is:

$$I_{pri} = I_L . S_{sw} = \frac{2}{\pi} \sum_{n=odd}^{\propto} \sum_{h=1}^{\propto} \frac{A_h}{n} [\cos(n\omega_s - h\omega_i)\, t] - \cos(n\omega_s + h\omega_i)\, t ….(7)$$

Equation(7) shows undesirable DC component of transformer winding current when $n\omega_s = h\omega_i$, but it can be neglected if the switching frequency is much higher than the frequency of input voltage.

VI. 4-step switching strategy

Electronic transformer has difficulties to commutate inductive load current from one bi-directional switch to another due to finite switch on/off time. Since the on/off operation of semiconductor switch requires delay time, an overlap between switching may cause short-circuited to the source input voltage and results in interrupting inductive load current. Hence,

snubber circuits are required on input and output sides. To control each semiconductor switch of any bi-directional switch independently, 4-step switching strategy is applied. The approach depends on polarity of input voltage or load current.
With an inductive load, switching operation can be divided into 4 modes according to the polarity of input voltage and load current as following.
Mode 1: Vi > 0; I_L> 0
Mode 2: Vi > 0; I_L< 0
Mode 3: Vi < 0; I_L> 0
Mode 4: Vi < 0; I_L< 0
The operation of 4-step switching sequence is divided into voltage and current reference mode according to the reference signal.

A. Voltage reference mode

Voltage reference mode uses input voltage polarity as the reference signal. Therefore, switching sequences of operation mode 1 and 2 are the same, and switching sequences of operation mode 3 and 4 are also the same.

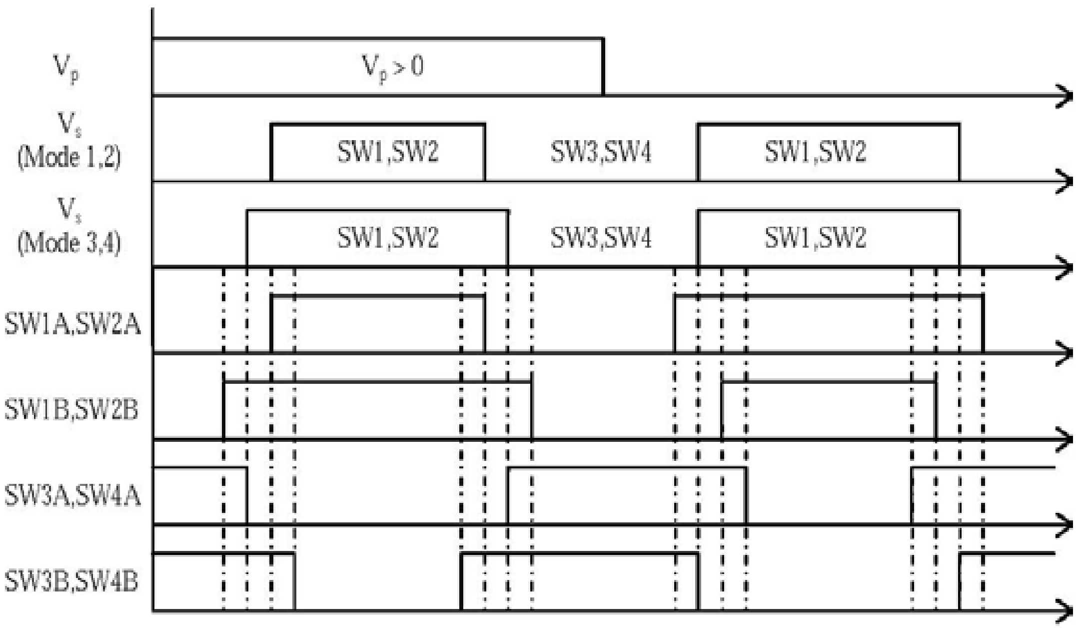


Fig.5 Example of gate signals by 4-step switching voltage reference mode.

B. Current reference mode

Current reference mode uses load current polarity as a reference signal. Therefore, switching sequences of operation mode 1 and 3 are the same, and switching sequences of operation mode 2 and 4 are also the same. The example of gate signals in current reference mode is shown in Fig. 7 where V_p represents load current polarity as reference signal, and V_s represents switch conduction state.

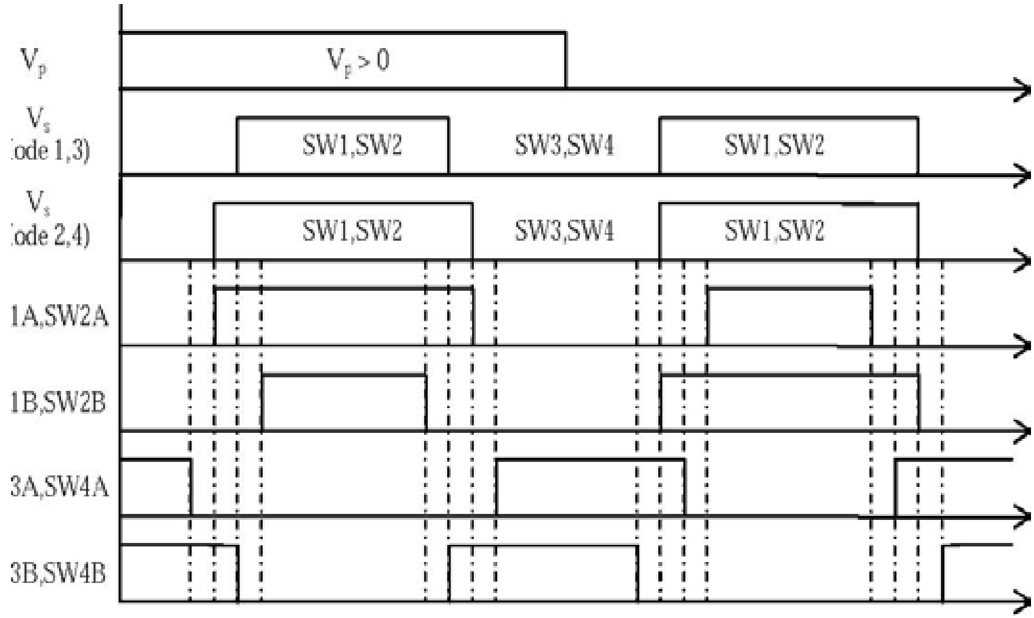


Fig.6. Example of gate signals by 4-step switching current reference mode.

VII. Conclusion

In this chapter, concept of electronic transformer system has been presented. Advantages and drawback of IUT are discussed. Operation of a transformer at high frequency has been discussed. Size of transformer can be reduced by this technology. Topologies of electronic transformer system employing primary and secondary converters were described and analyzed. The 4-step switching strategy allows safe commutation without snubber circuits, which losses can be reduced.

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