

Tapped inductor for switched-mode power converters

K.W.E.Cheng

Power Electronics Research Centre, Department of Electrical Engineering
The Hong Kong Polytechnic University
Hung Hom, Hong Kong
Email: eeecheng@polyu.edu.hk

Abstract: The tapped converter of the classical switched-mode power converter is an extension of the conventional switched mode power converters. Using the tapped configuration, the control parameter of the converter can be using tapping. It is found that the conversion has a very wide range of variation as compared with before. The paper introduces this basic concept to give readers a broader understanding of this classical method of power conversion.

Keywords: tapped inductor, switched-mode., power supply

I. INTRODUCTION

Classical switched mode power converters has been studied extensively and used in industrial products. They can be classified as Buck, Boost and Buck-Boost for the basic topology in which single inductor is presented and also Cuk, Sepic and Zeta for higher order topology which two inductors are presented in the circuit [1]. One of extension of the converters is reported using tapped-inductor in which the tapping of the inductor is connected to other components such as main switching device, freewheeling diode, input or output rails [2]. The converters have been reported as WJ converter [3] which is a Buck derived version. The converter can also be transformed to an inversion mode to provide positive and negative voltage. The converters has been

classified into Transistor-tapped, diode tapped and rail-tapped and the associated equations of the voltage conversion ratio of the converters have been reported. It is interesting to for readers understand properly the behavior of the voltage conversion characteristics among different topologies, the limitation and the associated boundary condition of the discontinuous mode.

Using a tapped inductor, it forms an additional control parameter for the voltage conversion. As the tapped inductor is similar to an auto-transformer, the energy is stored in the inductor when the transistor is turned on and is delivered to the output through the diode. Classical, the total stored energy during the transistor excitation is delivered to the output [5], using the tapped inductor, the output energy can be transformed into required voltage level.

II. THE BASIC BUCK TOPOLOGY

A. Principle of operation

The basic topology consists of 4 components which are active switching devices, diode, inductor and output capacitor. The nomenclature of transistor-tapped is referred to the tapping of the inductor is connected to the active devices. Similar definition is used for the diode tapped and rail tapped.

The derivation of the voltage conversion is using the

invariance of the mmf of the inductor during the switching. Fig. 1 shows the buck converter. Three topologies are shown, namely, switched-tapped, diode-tapped and rail-tapped. The on and off stages of the converter are shown that indicates the current flows. The current flow in the inductor is controlled by the transistor Q and is then continuous to flow through the diode through another terminal after the transistor is turned off. The current amplitude changes with the transformer turns ratio.

The current through the tapping or terminal can easily be identified by the winding direction or in the circuit the dot notation.

The equivalent circuits of each topology is shown in order to explain the operation of the circuit and the current flow in the tapped inductor during the on and off stage operation of the circuit.

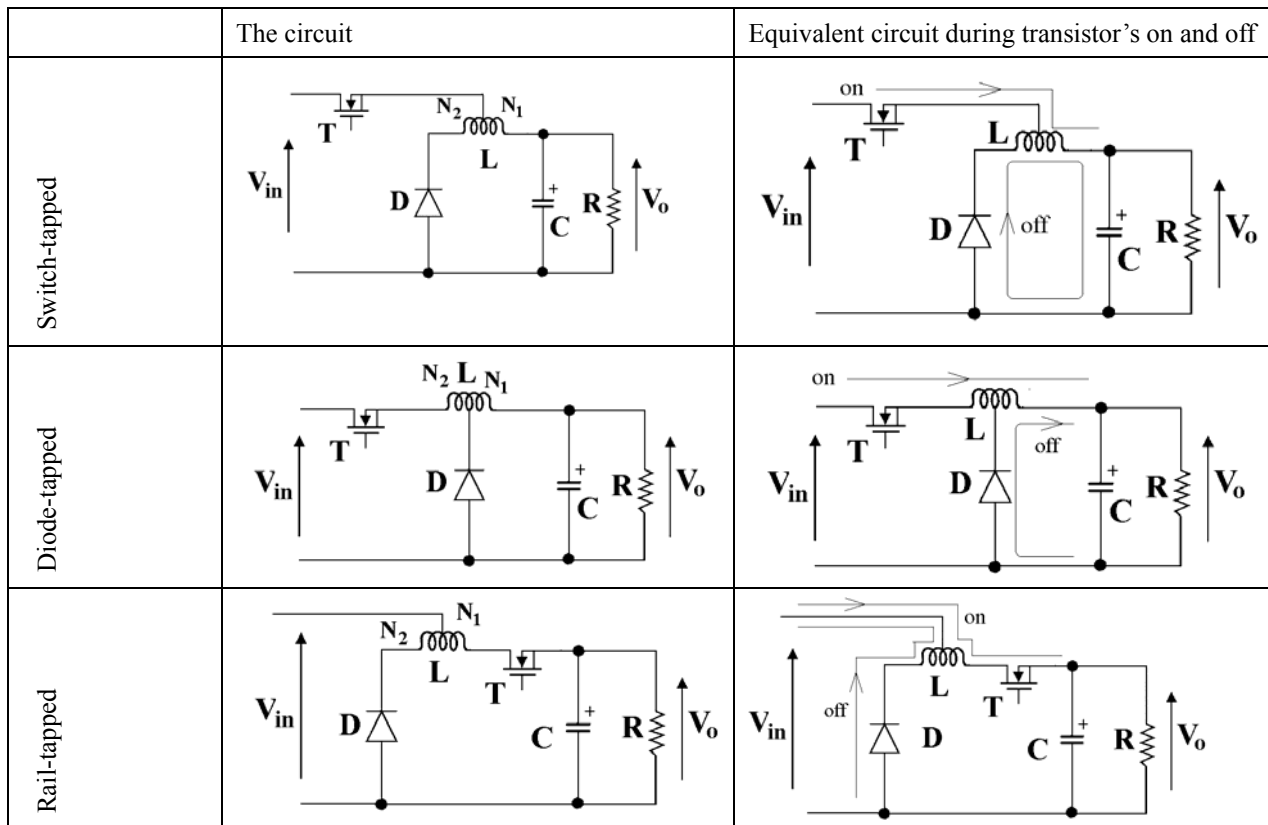


Fig 1: The 3 basic topologies for buck version the tapped-inductor converter

The voltage conversion ratio can be considered by the balance of the mmf during the on-state and off state.

The increase in mmf during the on state in general is:

$$M_{on} = N_{on} \frac{V_{Lon}}{L_{on}} DT_s \quad (1)$$

$$M_{off} = N_{off} \frac{V_{Loff}}{L_{off}} (1 - D) T_s \quad (2)$$

Where M_{on} is the increase in on-state mmf, M_{off} is the increase in off-state mmf, N_{on} is the number of turns excited during on-state, N_{off} is the number of turns

excited during off-state, L_{on} is the inductance for the N_{on} and L_{off} is the inductance for N_{off} .

The above parameters for the buck version have been tabulated in Table 1:

Table 1: The on and off state parameter for the mmf equations-

Topology	N_{on}	N_{off}	V_{Lon}	V_{Loff}
Switch-tapped	N_1	$N_1 + N_2$	$V_{in} - V_o$	V_o
Diode-tapped	$N_1 + N_2$	N_1	$V_{in} - V_o$	V_o
Rail-tapped	N_1	N_2	$V_{in} - V_o$	V_o

The voltage conversion ratio has been derived using (1) and (2) and is tabulated in Table 2.

Table 2: The voltage conversion V_o/V_{in} of the buck converter

Topology	Buck	k approach 1	k approach 0
Switch-tapped (ST)	$\frac{D}{D(1-k) + k}$	D	1
Diode-tapped (DT)	$\frac{kD}{1 - D + kD}$	D	0
Rail-tapped (RT)	$\frac{D - k}{D(1 - k)}$	-	1

When k approaches 1, i.e. N_1 winding forms the entire inductor. For the ST and DT circuits, the circuit reduces to a classical buck converter. For RT circuit, when the circuit does not realize into a practical as the inductor will be impressed with chopping current.

On the other hand, when k approaches 0, ST circuit becomes a unity switched capacitor converter [7], DT circuit cannot be realized as the inductor will be experienced with discontinuous chopping current. RT circuit will reduce to a unity switched-capacitor circuit.

B. Transfer characteristics

The characteristics depend on both k and D . It is interesting to obtain the characteristics with variation in both k and D . Figs 2a, 2b and 2c show the characteristics for ST, DT and RT Buck converters respectively.

The ST and DT Buck converters still process of a Buck characteristic. The voltage conversion ratio varies between zero and one. For the ST circuit, as k increases, the voltage conversion ratio increases and approaches to unity as k approaches 1. All the conversion characteristic

point are higher than the conventional counterpoint $a=$ but less than unity. The tapped inductor acts as an autotransformer to provide another control factor for voltage conversion.

The DT circuit behaves as a reduced voltage Buck converter. All the characteristics vary between that of the classical one and zero. One of the obvious applications is to provide much lower conversion ratio than that of the classical Buck converter. It is also noticed that the ST and ST circuit characteristics fill up the characteristic window and ST fills up the upper half and DT fills up the lower half.

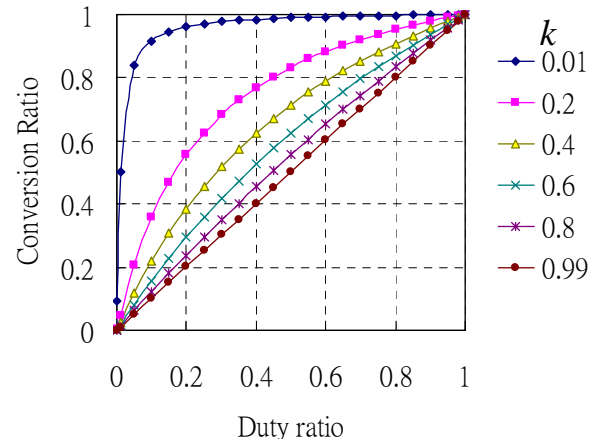


Fig 2a: Transfer characteristics for the ST Buck circuit

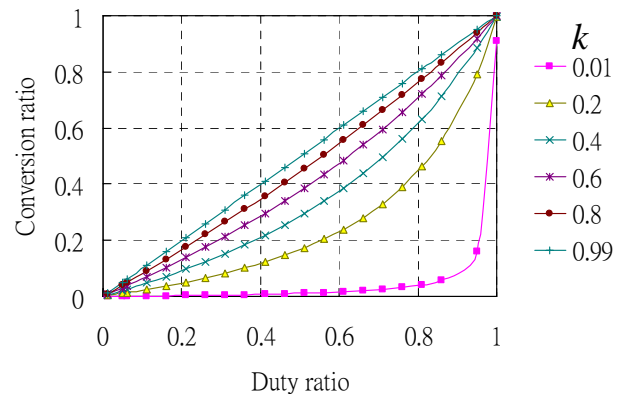


Fig 2b: Transfer characteristics for the DT Buck circuit

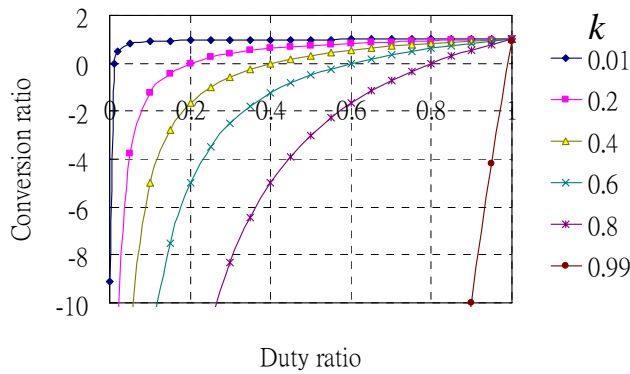


Fig 2c Transfer characteristics for the RT Buck circuit

III. THE OTHER BASIC TOPOLOGIES

The voltage conversion ratio for the Boost and Buck-Boost converters can be derived using the same method and their conversion ratio can be summarized in Table 3. Fig 3 shows the circuit and its equivalent circuit during the transistor's on and off stages. It can be seen that the inductor behaved as a auto-transformer and the energy stored during the on-stage is transferred to the diode circuit.

Table 3: Conversion ratio of the Boost and Buck-Boost versions

Topology	Boost	Buck-Boost
Switch-tapped	$\frac{D + (1-D)k}{k(1-D)}$	$\frac{-D}{k(1-D)}$
Diode-tapped	$\frac{D(k-1)+1}{1-D}$	$\frac{-Dk}{1-D}$
Rail-tapped	$\frac{k-D}{k(1-D)}$	$\frac{(1-k)D}{k(1-D)}$

Table 3: Limiting values of conversion ratio of the Boost and Buck-Boost versions

Topology	Boost		Buck-Boost	
	k approach 1	k approach 0	k approach 1	k approach 0
Switch-tapped	$\frac{1}{1-D}$	$\frac{D}{k}$	$\frac{-D}{1-D}$	$\frac{-D}{k}$
Diode-tapped	$\frac{1}{1-D}$	1	$\frac{-D}{1-D}$	0
Rail-tapped	$\frac{-D}{1-D}$	$\frac{-D}{k}$	0	$\frac{D}{k}$

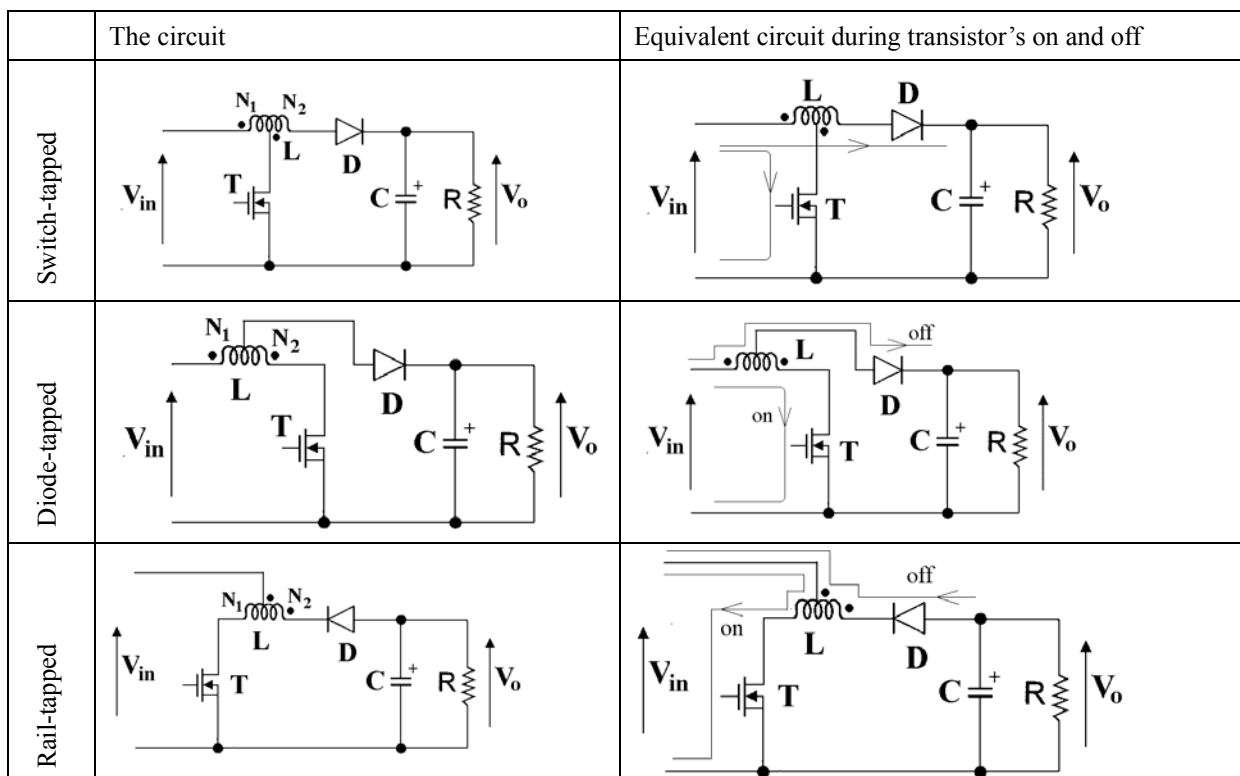


Fig 3: The 3 basic topologies for the boost version tapped-inductor converter

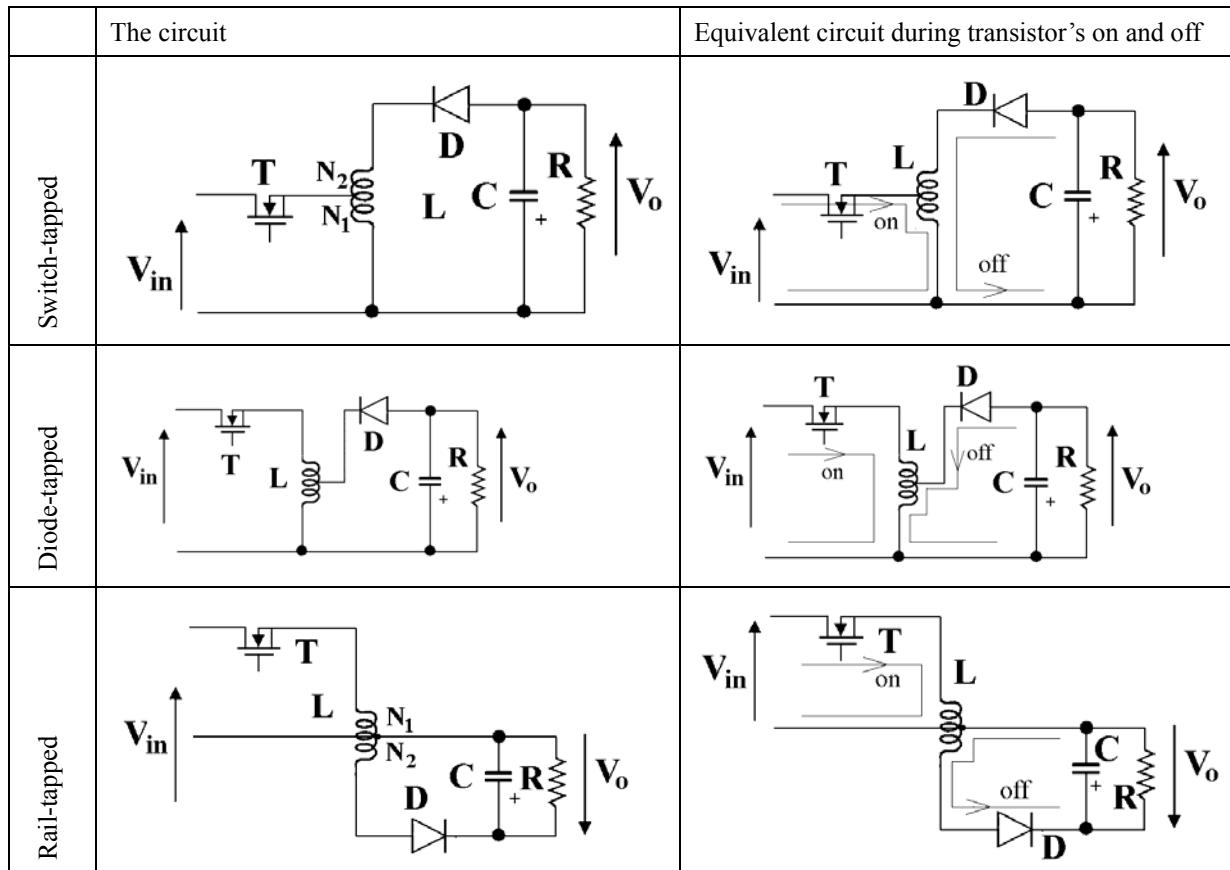


Fig 4: The 3 basic topologies for the buck-boost version tapped-inductor converter

A. Boost

Fig 3a 3b and 3c shows the voltage conversion characteristics of the ST, DT and RT Boost versions. Similar behaviours as the Buck version can be seen. Both ST and DT circuits have a conversion ratio higher than unity and their conversion ratio becomes that of the classical version $1/(1-D)$ when $k=1$. The conversion ratios of ST and DT circuits The conversion ratio becomes D/k when k approaches 0 for ST and RT circuits; becomes 0 for DT circuits. The characteristics for ST and DT circuits are complimentary in the characteristics window and are separated by the $1/(1-D)$ line.

However, the conversion characteristics RT circuit is different from the classical Boost version or the SR and DT circuits. The ratio is also less than 1 and extends to negative region.

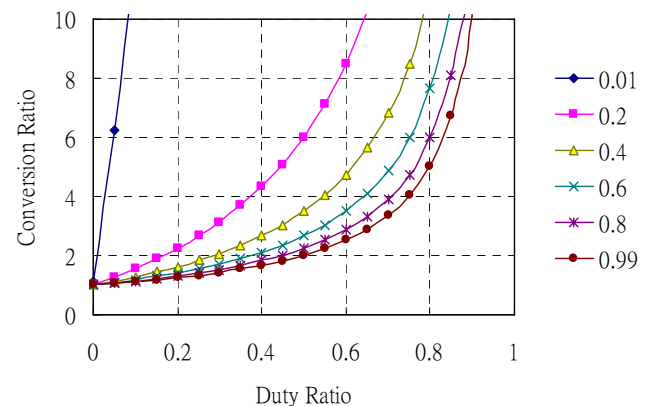


Fig 3c: Transfer characteristics for the ST Boost circuit

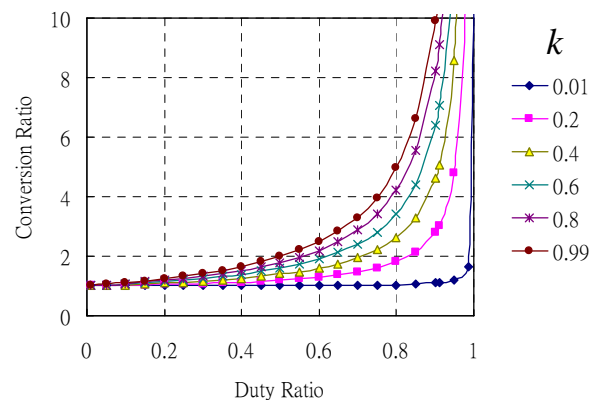


Fig 3b: Transfer characteristics for the DT Boost circuit

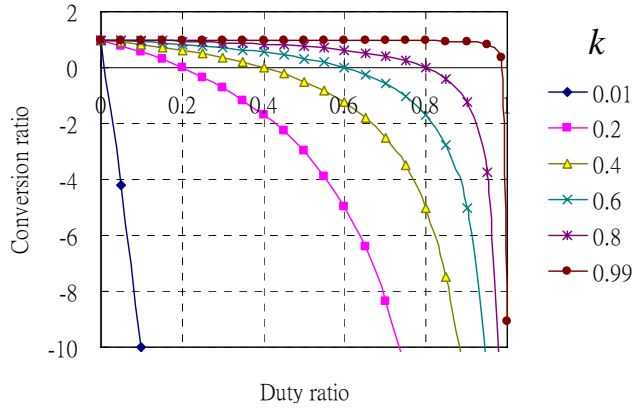


Fig 3c: Transfer characteristics for the RT Boost circuit

B. Buck-Boost

The characteristics of buck-boots circuit are shown in Fig 4a, 4b and 4c. They provide negative output voltage as the conventional counterpart. For the ST version, when $k < 1$, the conversion ratio (absolute value) increases. For the DT version, conversion ratio decreases as k decreases. For the RT version, it covers the whole range of conversion ratio as k varies between 0 and 1. The ratio is equal to that of the conversional counterpart when $k=0.5$.

The common characteristics for all three basic topologies are summarized as follows

- ◆ ST version gives higher conversion than that of the non-tapped conventional version
- ◆ DT version gives lower conversion than that of the non-tapped conventional version
- ◆ RT version gives both lower and higher conversion than the non-tapped conventional version
- ◆ The conversion ration of both ST and DT versions are equal to that of the non-tapped conversional version when $k=1$.
- ◆ The conversion ratio of RT versions for both Buck and Boost converters are equal to that of the non-tapped conversional version when $k=D/(D+1)$.

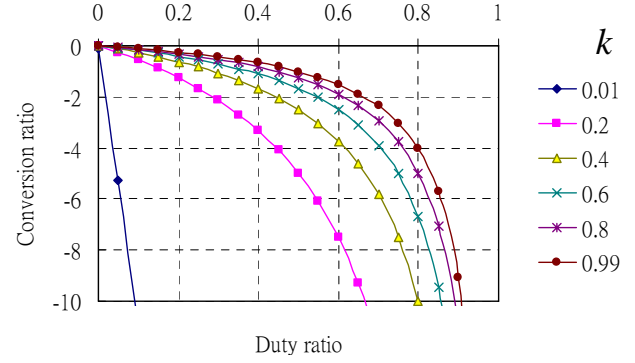


Fig 4a: Transfer characteristics for the ST Buck-Boost circuit

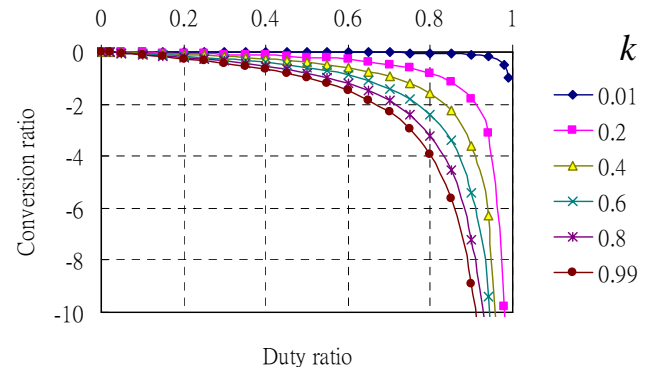


Fig 4b: Transfer characteristics for the DT Buck-Boost circuit

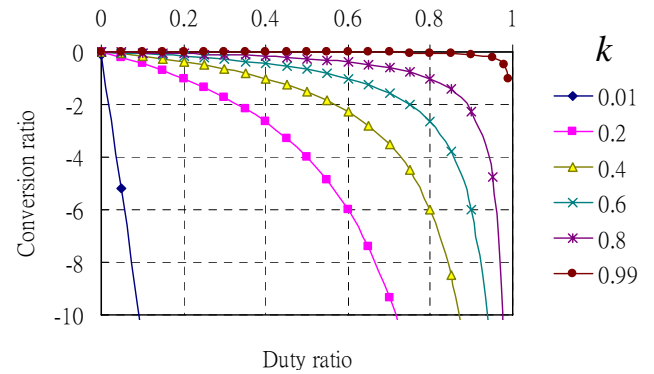


Fig 4c: Transfer characteristics for the RT Buck-Boost circuit

IV. CONCLUSION

The general characteristics for the tapped inductor switch-tap, diode tap and rail tap version for three basic converters have been examined. It has been found that the voltage characteristics of the converter have extended its non-tapped version and the transistor and diode tapped versions cover the whole conversion ratio characteristics window. Therefore the tapped converter can give a voltage variation of the voltage conversion.

It is also expected that the efficiency can be high using the trapped inductor techniques. The tapped conversion version has a capability for a number of applications in static power conversion such as intelligent clothing, battery charger, non-isolated power supply.

ACKNOWLEDGEMENT

The authors would like to thank the support of the Research Committee, Hong Kong Polytechnic University under the project G-YE17.

References

- [1] Cheng K.W.E., "Classical Switched-mode and resonant power converters, The Hong Kong Polytechnic University, ISBN: 962-367-364-7, Sep 2002.
- [2] Grant, D.A.; Darroman, Y., "Watkins-Johnson converter completes tapped inductor converter matrix", *Electronics Letters*, Vol. 39, Issue 3, 6 Feb. 2003 pp. 271 – 272
- [3] Grant, D.A.; Darroman, Y., "Watkins-Johnson converter completes tapped inductor converter matrix", *Electronics Letters*, Vol. 39, Issue 3, 6 Feb. 2003 pp. :271 – 272.
- [4] WJ, negative Grant, D.A.; Darroman, Y., "Inverse Watkins-Johnson converter - analysis reveals its merits", *Electronics Letters*, Vol. 39, Issue 18, 4 Sept. 2003, pp.1342 – 1343.
- [5] K.W.E.Cheng, "Investigation of the storage energy for classical switched mode power converters", *IEE Proceedings-Electric Power Applications*, Vol. 150, Issue 4, July 2003, pp. 439-446.
- [6] K.Yao, M.Ye, M.Xu, F.C.Lee, "Tapped-inductor buck converter for high-step-down DC-DC conversion", *IEEE Transactions on Power Electronics*, Vol. 20, No. 4, Jul 2005, pp. 7745-780.
- [7] Y.P.B.Yeung K.W.E.Cheng, S.L.Ho K.K.Law and D.Sutanto, "Unified analysis of switched-capacitor resonant converters", *IEEE Trans Ind. Electronics, Industrial Electronics*, *IEEE Transactions on* , Volume: 51 , Issue: 4 , Aug. 2004, pp.864 – 873.