Buck Regulators Without or with Magnetically Coupled Filters

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ABSTRACT: *This paper is intended to help control engineers and designers of high power industrial application such as engineers of traction motor control as well as control engineers and designers of very low power industrial applications such as designers of computer motherboards and other circuits using Infinity's LX166x family of buck regulator. The paper deals with the effect of replacing the smoothing filters without magnetic coupling used for reducing the ripple generated at the output of buck regulators by a new topology known as magnetically coupled filters. The main attention is focused on the analysis and the simulation of the two-phase parallel connection of buck regulator with magnetically coupled filters known as an interphase reactor or transformer. A comparison of the two-phase connections with smoothing filters without magnetic coupling or with magnetically coupled filters is then done. Actual criteria for comparison may be carried out from technical parameters and investment perspectives. Technical parameters are considered to be: Distribution of currents into phases and harmonic content (the amount of the ripple in the load current). Investment costs depend on demands to the material needed for designing the filters. The result of using the magnetically coupled filters is a progressive reduction of the harmonic content generated at the output.*

Keywords: Buck regulator, Filters, Smoothing chokes, Magnetic coupling, Double phase connection.

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1. Introduction

A Buck regulator is commonly used in applications such as powering microprocessors. They are ideal for converting a 5V-system to the 2V or so, at up to 20A that processors require. It is also widely used for traction motor control in electric automobiles, trolley cars, marine hoists, and mine haulers.

The main advantages of a buck regulator are high efficiency; relatively simple design; low switch stress and small output filter. The main disadvantages are possible over voltage if the main switch shorts and certain harmonic content at its output.

A D.C. - D.C. buck regulator converts directly from D.C. to D.C. and like an ac transformer, it is used to chopper down or chopper up a D.C. voltage source. Due to their ability to supply a continuously variable D.C. voltage, D.C. buck regulator made a revolution in modern industrial and control technology, with power levels ranging from fractional horsepower to several megawatts [1,2].

Because of the periodic function of the regulator, its output voltage and current contains harmonics [4]. This kind of harmonics affects the losses in the load and in the regulator and as a consequence of that, its control is more complicated. It needs special controllers and an additional control system.

In practice, Filters are used to reduce the level of harmonics but the size of these filters increases with the increase of harmonic content at input and output [5,6].

Usually, as a means of reducing the ripple generated at input and output, the buck regulator may compromise two or more channels in parallel. The outputs of these channels are combined through smoothing filters without magnetic coupling. The distribution of currents into phases is made by control systems – by soft proportional distribution of duty ratio of every channel. The switching of the regulators is then non-simultaneous, mutually out of phase by the time T/m (m is the number of phases, T is the operating period of the main switch). This kind of connection is called a multi-phase parallel connection of buck regulators with smoothing filters without magnetic coupling.

A better solution is obtained if a magnetic coupling of each two smoothing filters is introduced. This new topology of smoothing filters is known as magnetically coupled filters. The number of channels in this case must be even.

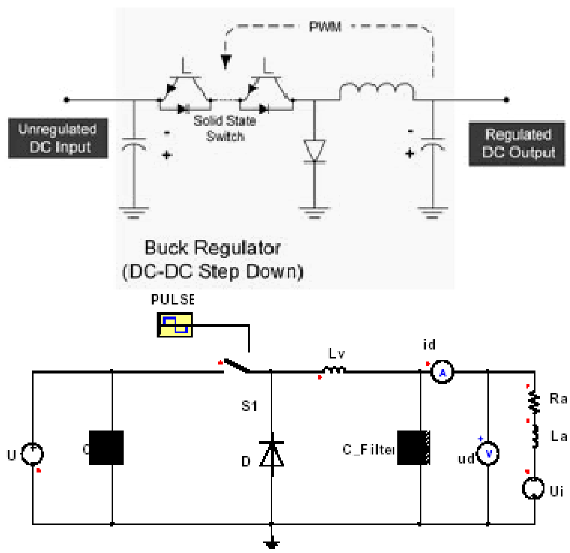
The result is a progressive reduction of the A.C. voltage and current component in the load on the output and in the supply on the input, and with little demands on the input smoothing filter. It also increases the power of the regulator, makes the control smooth and easy. It also increases the switching frequency of the regulator and by this way we surely reduce the size of the filters used at the input and at the output of the regulator.

This paper is organized as follows. Section II introduces the mathematical analysis and simulation for the two-phase connection with smoothing filters without magnetic coupling, section III introduces a new connection with magnetically coupled filters, and section IV proposes an overview about the design methodology of smoothing filters without magnetic coupling and magnetically coupled filters. Section V applies this methodology and the theoretical analysis obtained for the above mentioned variants of connection to compare between them.

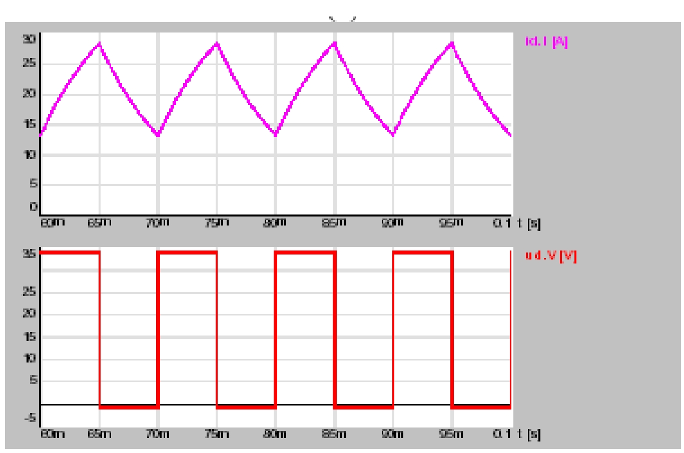
2. Buck regulator without magnetic coupling

A single-phase step-down buck regulator circuit is illustrated in Fig. 1a. The principle of operation of a buck regulator as shown in Fig.1a is currently known.

A step down regulator varies its average output voltage U_d that appears across the load which is relative to its input U, by varying the proportion of its operating time during which the output is connected to the input. In other words, the unspecified



(a)



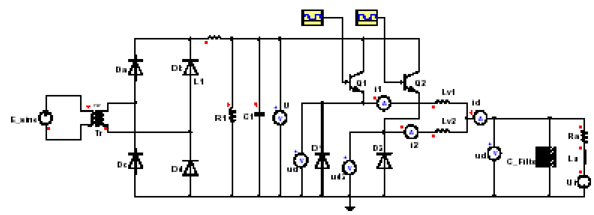
(b)

Figure 1. Buck regulator with its output voltage and current waveforms

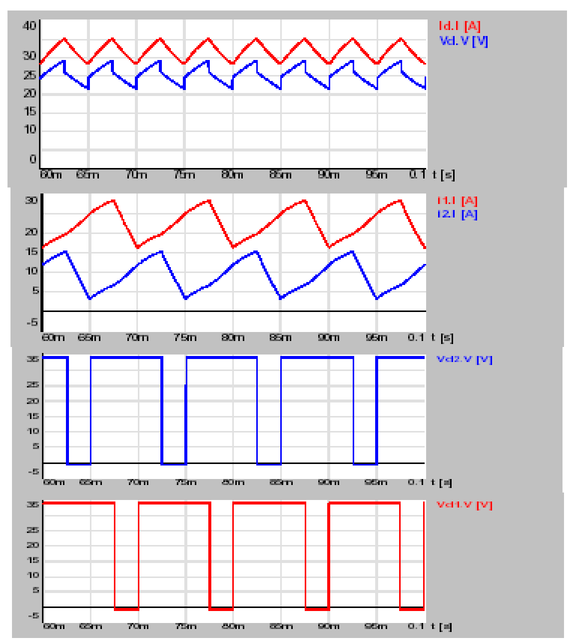
solid state switch as shown in Fig.1, operates with a regular periodic time T, and is closed for a time $T_2 = T - T_1$, $U_d = zU$, $z = T_1/T$, z is a switching ratio of the output ripple voltage ud.

A circuit diagram for a two-phase parallel connection of buck regulator with smoothing filters L_{v1}, L_{v2} without magnetic coupling is shown in Figure 2a.

Such regulator has two channels connected in parallel, Q_1, D_1 and Q_2, D_2. They are supplied via a single phase bridge rectifier and operating out of phase by the time T/m. The load is considered to be an inductor L_a, resistor R_a and an nternal voltage



(a)

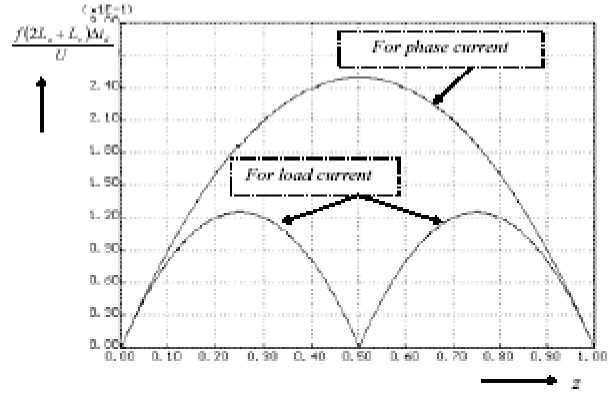


(b)

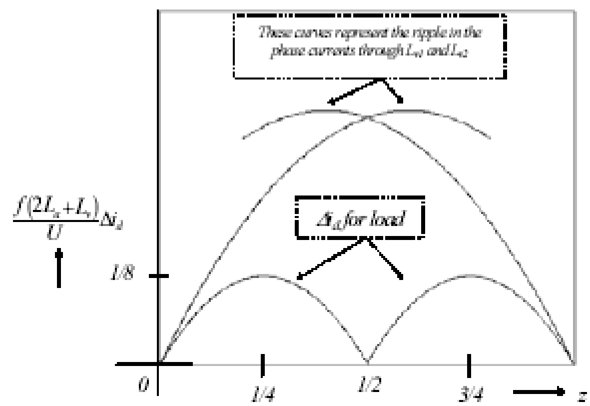
Figure 2. Simulation of Two-phase parallel connection with smoothing filters without magnetic coupling in Simplorer 6 ($1/2 \leq z \leq 1$): (a) Equivalent circuit. (b) Voltage and current waveforms

source U_i. However, the voltage and current simulation produced by this circuit is shown in Figure 2b. The input voltage U across resistor R_1 at the input terminals of these regulators is considered to be purely constant. The average value of the output voltage U_d is considered to be equal to the internal voltage Ui since the voltage drop across R_a is neglected throughout this paper. The output of every channel is combined with the load through a smoothing filter L_{v1}, L_{v2}. Input filter resp. output filter, L_1, C_1, R_1 resp. C_Filter will not be taken into consideration throughout this paper. The mean value of the currents of the parallel smoothing filters without magnetic coupling L_{v1}, L_{v2} must be equally distributed into these filters by control system, that is, by soft proportional distribution of duty ratio of every channel. Otherwise, currents of different values will flow into the phases as it is shown in Figure 2.

The peak-to-peak load ripple current Δi_d may be determined under the steady state condition (quasi-stationary state) of the regulator from the steep rise of the load current during the on-time T_1 of the main switch (IGBT, BJT transistor or MOSFET).



(a)



(b)

Figure 3. Dependence of Δi_d on z: a) $L_a = 0$, b) La <>0

This rise is obtained for $f = \frac{1}{T}$, $L_{v1} = L_{v2} = L_v$, $L_a = 0$ as follows:
When the main switch Q_1 is on, then:

$$i_1(t) = i_1(0) + \frac{1}{L_v}(U - U_i)t \tag{1}$$

When Q1 became off at the end of its on-time T_1, diode D_1 conducts the current i_1 and then:

$$i_1(t) = i_1(T_1) - \frac{U_i}{L_v}(t - T_1) \tag{2}$$

The peak-to-peak ripple of current i_1 during its on-time T_1 is then obtained as follows:

$$\Delta i_1 = \frac{U - U_i}{L_v} T_1 \tag{3}$$

Similar expressions may be obtained for i_2. The relationship between the load current and the phase currents is:

$$i_d = i_1 + i_2 \tag{4}$$

The ripple of load current i_d may be determined for $0 \le z \le {}^1/_2$ when one main switch is on and the other is off as follows:

$$\Delta i_d = \frac{U - U_i}{L_v} T_1 + \frac{U_i}{L_v} T_1 \tag{5}$$

And thus:

$$\Delta i_{dM} = \frac{U}{f(2L_a + L_v)}(1 - 2z)z \tag{6}$$

For when both switches are on, Δi_d may be obtained as follows:

$$\Delta i_d = 2\frac{U - U_i}{L_v}\left(T_1 - \frac{T}{2}\right) \tag{7}$$

And thus:

$$\Delta i_d = \frac{U}{f\, L_v}(3z - 2z^2 - 1) \tag{8}$$

Where $z = \frac{T_1}{T}$ is called duty ratio of the regulator and the maximum peak-to-peak ripple Δi_{dM} occurs according to eq. (6) when z = 1/4 and according to eq. (8) when z = 3/4 :

$$\Delta i_{dM} = \frac{U}{8\, f\, L_v} \tag{9}$$

If we take into consideration the effect of the voltage drop on load inductance $L_a\left(u_{La} = L_a\frac{di_d}{dt}\right)$, and after repeating the analysis under this condition we get:

$$\Delta i_{dM} = \frac{U}{8\, f\left(2L_a + L_v\right)} \tag{10}$$

The main results for Δi_d with are illustrated in Figure 3.

3. Buck regulator with magnetically coupled Filters and Demands to materials of filters

The scheme is shown in Figure 4. The analysis of this type of regulators can be best explained under a condition of neglected leakage inductance. It has no considerable sense for the analysis of this regulator. The two halves of filters winding have identical numbers of turns *N*.

If the magnetizing inductance of the magnetically coupled filters is infinite ($L_\mu \to \infty$), i.e. the magnetizing current $i_\mu \to 0$, $R_a = 0$, $L = L_a + L_v$, then must be:

$$N i_1 = N i_2 \tag{11}$$

$$i_d = i_1 + i_2 \tag{12}$$

And

$$i_1 = i_2 = \frac{i_d}{2} \tag{13}$$

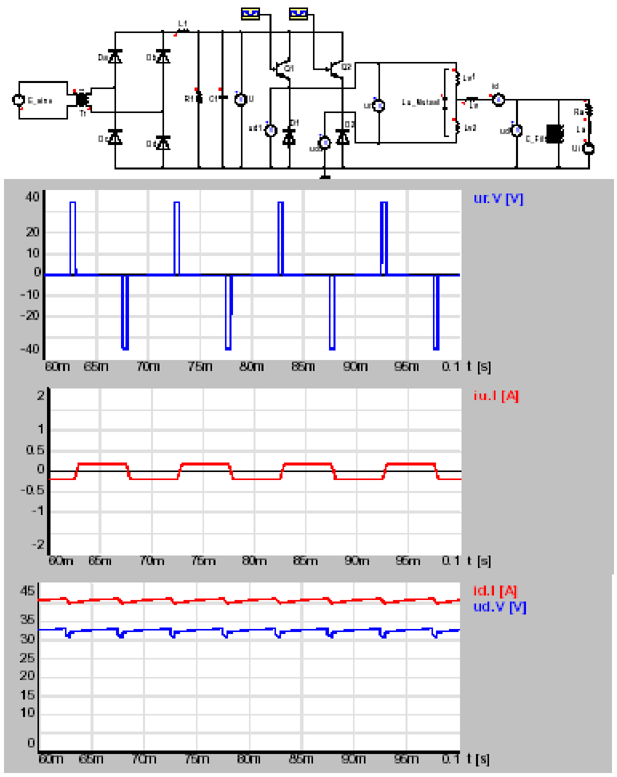


Figure 4. Schematic diagram of a buck regulator with magnetic coupling and voltage-current simulation produced in Simplorer 6

In a certain interval, *if* Q_1 is closed (conducting) and Q_2 is opened, then, i_1 flows into Q_1 and because of the magnetic coupling a same big current i_2 flows into D_2, and each channel carries approximately half the output current continuously and the voltages across the two halves of the winding are substantially equal. Therefore, there will be no need for controllers for distributing the currents into phases as in the case of connection with smoothing filters without magnetic coupling.

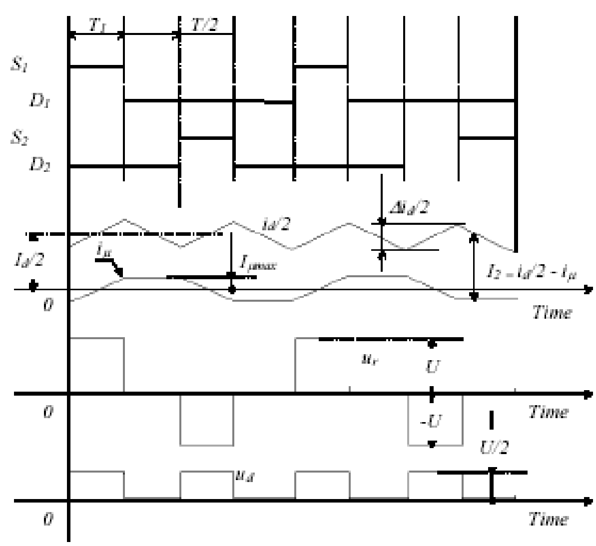


Figure 5. waveforms in a two-phase buck regulator with magnetically coupled filters
(a). Load current and voltage, i_d and u_d and voltage u_r across the magnetically coupled filters

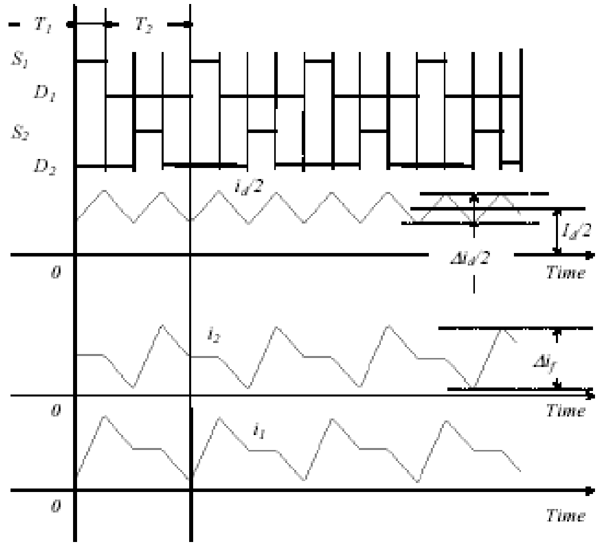


Figure 5b. Phase currents i_1, i_2

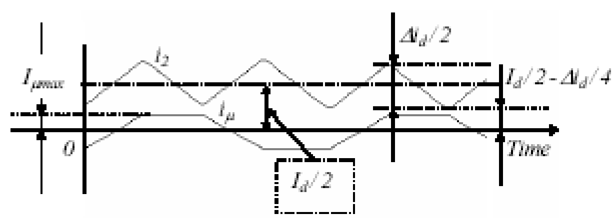


Figure 5c. An example of big value of i_μ, nearly equal to i_2 which may result in an interrupted phase current

The voltages u_1 and u_2 are determined by a state of switching. From Figure 4 and according to Kirchoff's laws, four cases can be occurred:

1. Q_1 opened, and D_1 closed then u_1=0,
2. Q_1 closed, and D_1 opened then $u_1=U$.
3. Q_2 opened, and D_2 closed where u_2=0.
4. Q_2 closed, and D_2 opened then $u_2=U$.

The voltage across the magnetically coupled filters can be determined with respect to the above mentioned considerations as follows:

$$u_r = u_1 - u_2 \tag{14}$$

However the voltage that appears across the load is affected by the voltage of magnetically coupled filters as follows:

$$u_d = u_1 - \frac{u_r}{2} = u_2 + \frac{u_r}{2} = \frac{u_1 + u_2}{2} \tag{15}$$

If the magnetizing inductance of magnetically coupled filters L_μ is real, it causes a magnetizing current i_μ to flow into the magnetically coupled filters from one regulator group output terminal to the other and to be superposed to the D.C. current component $I_d/2$ which flows into each halve of the winding of magnetically coupled filters:

$$i_1 = \frac{I_d}{2} + i_\mu \tag{16}$$

$$i_2 = \frac{I_d}{2} - i_\mu \tag{17}$$

The voltage and current waveforms are illustrated for finite L_μ and in Figures 4, 5. From Figure 5 it can be concluded that:

$$\frac{I_d}{2} - \frac{\Delta i_d}{4} - I_{\mu\,max} > 0 \tag{18}$$

And for $0 \le z \le {}^1/_2$ when Q_1 and D_2 are conducting (Q_2 is off) we may write for the load current the following expression, ($U_d = U_i$):

$$i_d = i_d(0) + \frac{\frac{U}{2} - U_i}{L} t = i_d(0) + \frac{U - 2U_i}{2L} t \tag{19}$$

And thus

$$\Delta i_d = \frac{U}{2fL}(1-2z)z \tag{20}$$

For 1/2 < z <1 when both main switches are on we may write:

$$\Delta i_d = \frac{U - U_i}{L}\left(T_1 - \frac{T}{2}\right) \tag{21}$$

Therefore:

$$\Delta i_{dM} = \frac{1}{16fL} \tag{22}$$

The extreme of the above mentioned expressions of eq. (21) and (22) occurs at z = 1/4 or z = 3/4. Maximum of Δi_d is then:

$$\Delta i_{dM} = \frac{1}{16fL} \tag{23}$$

In region 1/2 < z <1 we can get for Δi_d a similar characteristic as it is shown in Figure 6.

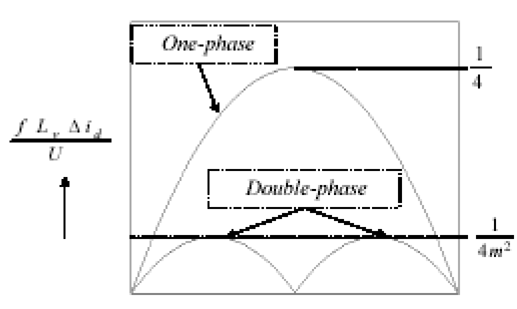


Figure 6. Two-phase connection of buck regulators with magnetically coupled filters: Dependence of Δi_d on z

From the waveforms of u_r in Figure 5a it may be found that:

$$2 I_{\mu\max} = \frac{U}{L_\mu} T_I \tag{24}$$

The maximum value of $I_{\mu m}$ occurs when:

$$I_{\mu\,max} = \frac{U}{4 f L_\mu} \tag{25}$$

4. Design consideration

Next problem will be to find a simple method for determining demands to materials of magnetically coupled filters to compare them with other connections of buck regulator. For this purpose let's consider a coil with a number of turns *N,* wrapped around a rectangular ferromagnetic core with a cross-sectional area S_F and current *i* flowing into it.

Then, under the condition of linear magnetization curve of the core with the coil and a neglected leakage flux, we can write for the inductance *L* of the coil, the possible maximum value of the non-saturation magnetic flux density B_s within the ferromagnetic core and the corresponding maximum value of the magnetization current $I_{\mu max}$ the following expression:

$$L I_{\mu max} = N S_{Fe} B_S \tag{26}$$

Concerning the coil, it is necessary to dimension its winding with respect to the maximum effective value of the current that can flow into it. By adding this current to (16) and after rearrangement we can get:

$$\begin{aligned} L I_{\mu\,max} I_{efM} &= N B_s S_{Fe} I_{efM} \\ L I_{\mu\,max} I_{efM} &= N B_s S_{Fe} \sigma S_{vod} \\ &= \sigma B_s S_{Fe} S_{cu} = K_L \end{aligned} \tag{27}$$

Wherein σ is the admissible density of the current I_{efM} that is flowing through the wire of the coil of a cross-sectional area S_{vod}, and S_{cu} is the cross-sectional area of the total winding of the coil and it may represent the material used in making the winding and S_{Fe} represents the material needed for making the core.

In the case of a simple smoothing choke (filter) $I_{\mu max}$ respectively I_{efM} are considered to represent the maximum instantaneous respectively the maximum effective value of the same current that is flowing through the coil of the filter. Concerning the

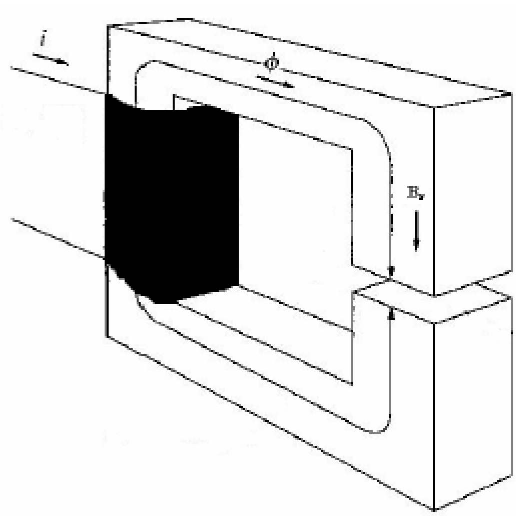


Figure 7. Magnetic core with coil

magnetically coupled filters I_{efM} is considered to be the possible maximum effective value (rms) of the current flowing into one phase (channel) and $I_{\mu max}$ is the possible maximum instantaneous value of the magnetization current i_u.

Therefore, parameter K_L in (27) may be considered as an approximate view of economical costs of the amount of materials needed for making smoothing filters or magnetically coupled filters.

5. Simulation Results

This section covers the criteria necessary for doing a mutual comparison of the previously analyzed connections of buck regulator. These criteria are neatly arranged in table 1 as follows:

Demands to materials of filters without magnetic coupling or with magnetic coupling K_L.

Demands to secured and stable control system for equally distributing the currents into phases.
In each of the three columns are given relations that are essential for comparing the previously mentioned different types of connection of buck regulator. In particular, they are inductance L_v of the smoothing choke connected directly to the load in the case of a fundamental connection of the regulator or with a magnetic coupling (Fig. 1 and Fig. 4), the inductances of smoothing chokes L_{v1} and L_{v2} shown in Figure 2 and the magnetization inductance L_u resultant from mutual magnetic coupling between the two filters (smoothing chokes) of the interphase transformer shown in Figure 4.

The expressions for estimating parameter K_L representing the material demands for chokes and interphase transformer is shown in table 1 with only a prerequisite for the use of a ferromagnetic core.

All parameters listed in the table are mainly dependent on the supply voltage U of the regulator, the switching frequency f and on the maximum peak-to-peak load ripple current Δi_{dM}.

Concerning the material demands and other parameters such like the inductances of filters and the maximum peak-to-peak load ripple current that are necessary for comparing different variants together, they may be obtained from the previous analysis as follows:

The inductance of the smoothing choke of a fundamental connection of buck regulator shown in figure 1 may be obtained ([1], [2]) as follows:

$$L_v = \frac{U}{4f\Delta i_{dM}} - L_a \quad \textbf{(28)}$$

The value of the inductance of one filter (smoothing choke) in the case of two-phase variant without magnetic coupling is:

$$L_v = \frac{U}{8f\,\Delta i_{dM}} - 2L_a \quad \textbf{(29)}$$

where where $L_{v1} = L_{v2} = L_v$.
Concerning the two-phase variant with magnetically coupled filters ($L = L_v + L_a$), the smoothing choke connected directly to the output load is given as**:**

$$L_v = \frac{U}{16f\,\Delta i_{dM}} - L_a \quad \textbf{(30)}$$

The selection of the appropriate value for the inductance of a certain filter should satisfy the critical inductance condition which happens when the current through the inductor decays to zero just prior to the next on time of the regulator switch. This occurs at the boundary between continuous and discontinuous operation which occurs when, for any condition of input voltage or output current, the inductor current decays to zero before the next on time of the regulator switch. This is not included in this paper.

The expression for demands to the materials of a simple smoothing choke (filter) in the case of a fundamental connection (Figure 1) may be simplified, if we put, $I_{dM} = I_{efM} = I_{\mu\max}$ where I_{dM} is the possible maximum value of the average load current I_d which can flow through the load. And thus:

$$K_L = L_v I_{dM}^2 \quad (31)$$

For the two phase connection without magnetic coupling the current passing through each phase is $\frac{I_{dm}}{2} = I_{efm} = I_{\mu max}$, therefore we get that:

Parameters		REGULATOR		
		SINGLE PHASE (FIG. 1)	**DOUBLE PHASE (FIG. 2)**	**DOUBLE PHASE (FIG. 3)**
Choke	NO. OF PIECES	1	2	1
	L_V	$\frac{U}{4f\Delta i_{dM}} - L_a$	$\frac{U}{8f\Delta i_{dM}} - 2L_a$	$\frac{U}{16f\Delta i_{dM}} - L_a$
	K_L	$L_v I_{dM}^2$	$L_v \frac{I_{dM}^2}{4}$	$L_v I_{dM}^2$
Interphase transformer	NO. OF PIECES	–	–	1
	L_μ	–	–	$\frac{U}{4f I_{\mu max}}$
	K_L	–	–	$\frac{L_\mu I_{\mu max} I_{dM}}{2} = \frac{U I_{dM}}{8f}$

Table 1. Comparison of different variants of buck regulator

$$K_L = L_v \frac{I_{dM}^2}{4} \tag{32}$$

In the case of a two-phase connection with magnetically coupled filters we should take into consideration the following things:

The inductance of the smoothing choke connected directly to the load is considered to be $_{av}LL$ and its K_L is the same as in the case of a fundamental regulator (Figure 1):

$$K_L = L_v \frac{I_{dM}^2}{4} \tag{33}$$

The magnetization inductance L_μ of the interphase transformer is determined with respect to the possible maximum value of magnetization current $I_{\mu max}$, obtained from equation 25 as it is shown in the table. It is evident from equation 25 and figure 5c that in order to avoid the mode of interrupted phase currents, $I_{\mu max}$ should satisfy the following condition:

$$i_\mu \le \frac{i_d}{2}, I_{\mu max} \le \frac{I_d}{2} - \frac{\Delta i_d}{4} \tag{34}$$

The load current i_d due to interphase transformer can never be interrupted.

The expression for the material demands for the magnetically coupled filters may be simplified, if we take into consideration that $I_{efM} = \frac{I_{dM}}{2}$ and $I_{\mu max}$ is the maximum value of the magnetization current flowing through both windings of the interphase transformer. Thus**:**

$$\frac{L_\mu I_{\mu max} I_{dM}}{2} = \frac{U I_{dM}}{8f} \tag{35}$$

In Figure 8 it is shown how the demands to the material change with the increase in the regulator switching frequency *f*.

The analysis and simulation prepared in previous sections undoubtedly show that more positive results give in this case the connection with magnetically coupled filters. There is no need here to equalize the distribution of currents into the parallel connected phases by use of control system and it needs more less amount of materials to be constructed.

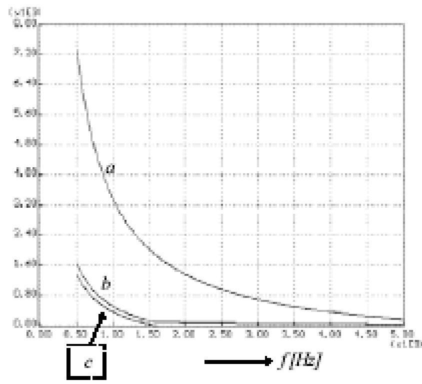


Figure 8. Plot of KL versus switching frequency f for: (a) single phase connection, (b) with magnetic coupling, (c) without magnetic coupling

6. Conclusion

Different variants of buck regulators with or without magnetically coupled filters are briefly proposed and analyzed. Moreover, demands to the material for making the filters are carried out. However, a mutual comparison of the parallel two-phase variants of connection of buck regulators for two-phase connection without magnetic coupling and with magnetically coupled filters is performed. The single phase variant is included in table 1 just to make the comparison more comprehensive.

There are mentioned in section IV the actual expressions, and values which can be used for mutual comparison of these variants.

The expressions and results obtained in this section and shown in table 1 objectively lead to the following conclusion:

One-phase variant may be given a priority when it is not necessary to use the parallel connection of devices.

The variant with magnetically coupled filters gives with respect to the accruing *f* which is a present trend more favorable results than the variant without magnetic coupling. Increasing frequency results in a decrease of the demands to the material as it is shown in Figure 8.

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