ISSN 1407-7345

ENERĢĒTIKA UN ELEKTROTEHNIKA
POWER AND ELECTRICAL ENGINEERING

2008-22

THE DOUBLE LINK LC FILTERS FOR PULSE REGULATION SYSTEMS

DIVPAKĀPJU LC FILTRI IMPULSREGULĒŠANAS SISTĒMĀM

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Keywords: pulse, magnitude, oscillations reactor, frequency, ratio, weight

INTRODUCTION

In the pulse regulation systems of DC voltage it's necessary to obtain a smooth current of DC source [1,2,3], especially for transport systems with catenaries grid. For obtaining of that an input LC filters are applied. It's shown in [2,3,4] that necessary parameters of the single link filter for step-down converter can be calculated as

for capacitor

$$C_{(1)} \geq \frac{I_{LD} \times D(1-D)}{[\Delta U] \times f} \quad ; \tag{1}$$

for inductance

$$L_{(1)} \geq \frac{I_{LD} \times D(1-D)}{8 f^2 \times L \times C \times [\Delta I]} \, , \tag{2}$$

where I_{LD} is DC component of load's current, D – duty ratio of pulse switch, f – switching frequency, [ΔU] and [ΔI] are an admissible values of full scale oscillations respectively for capacitor's voltage and source current.

Because size and weight of reactive elements are very high and depends directly on values of L and C it's necessary to find a solutions allowing to decrease ones. One of possibilities is application of the double link LC filters [3]. This paper is examining proposed solution on respect to a weight for different modes of pulse realization – for Step-down (BUCK) and Step-up (BOOST) converters.

EVALUATION OF FILTERS FOR BUCK CONVERTERS

Above presented equations are obtained assuming an output current of the filter as rectangular pulse with switching frequency f , ratio $0 \le D \le 1$ and magnitude equal to the load's current (Fig.1). Input filter can be installed also applying two LC links (Fig.2). In this case oscillation range of voltage across the capacitor C_2 can be calculate applying (1) but oscillations of current of reactor L_2 – applying (2). Voltage oscillations of the first capacitor C_1 can be calculate assuming at first step that current of reactor L_1 is absolutely smoothed. Then oscillations depend on the alternating component of the current i_{L2} which can be accepted as sinus shape. Then

$$\Delta U_{C1} = \frac{\Delta I_{L1}}{2\pi f C} = \frac{\Delta U_{C2}}{16\pi f^2 L_2 C_1} \quad . \tag{3}$$

In similar way can be find equation for calculation of full range oscillations of source current

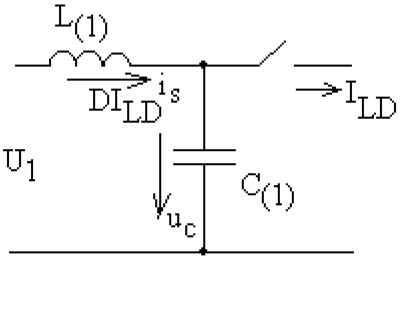
$$\Delta I_{s(2)} = \Delta I_{L1} = \frac{\Delta U_{C1}}{2\pi f L_1} = \frac{\Delta U_{C2}}{32\pi^3 f^3 L_1 L_2 C_1} \quad . \tag{4}$$

As it's seen a full range of oscillations of source current for double link filter is much smaller than for a single link one and smoothing relation

$$\frac{\Delta I_{s(2)}}{\Delta I_{s(1)}} = \frac{8}{315.5 f^2 L_1 C_1} \quad , \tag{5}$$

i.e. application of the double link filter in respect to smoothing is very efficient solution. At constant accepted range of source current oscillations and same for both filters switching frequency relation of product of reactive elements is

$$\frac{L_1 L_2 C_1 C_2 (2)}{LC(1)} = \frac{1}{30.9 f^2} \quad . \tag{6}$$



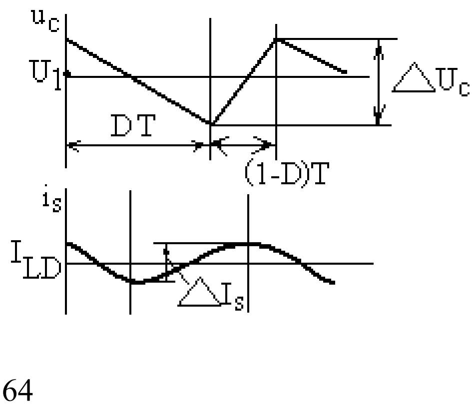


Fig.1. Scheme of the single link LC filter in BUCK converter and diagrams of its capacitor voltage and reactor's current oscillations

Nevertheless must be considered increasing of number of reactive elements and its influence on weight of filter. If weight of reactor can be assumed as $G_L=k_{GL}$ L, but capacitor – as $G_C=k_{GC}$ C then for single link filter the optimal reactor in respect to weight has

$$L_{opt(1)} = \sqrt{\frac{k_{GC} \times LC(1)}{k_{GL}}} = \sqrt{\frac{k_{GC} I_{LD}}{k_{GL} 32 f^2 [\Delta I_s]}} \tag{7}$$

but for double link at $L_1=L_2=L$ and $C_1=C_2=C$

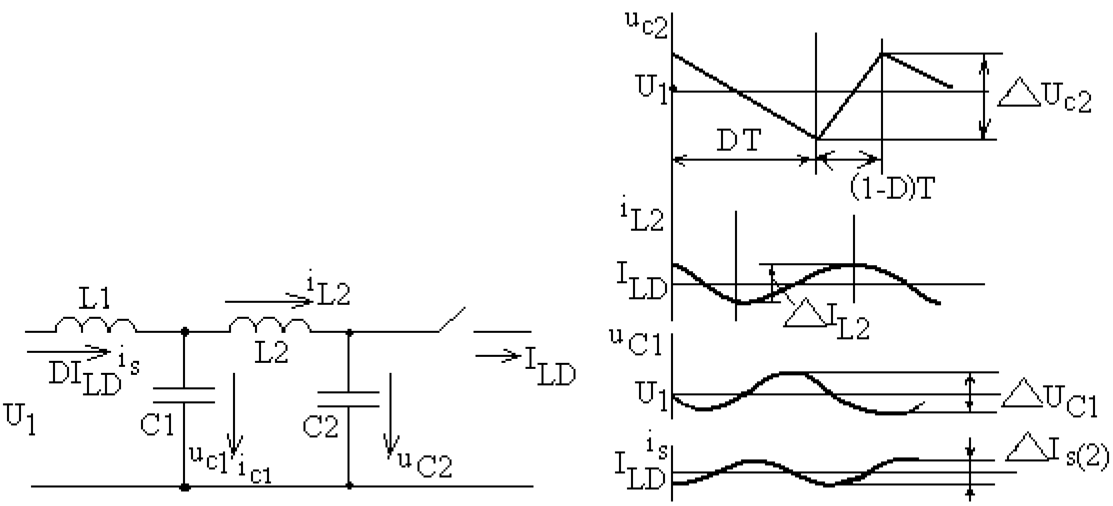


Fig.2. Scheme of the double link LC filter in BUCK converter and diagrams of signal oscillations for elements of filter

$$L_{opt(2)} = \sqrt{\frac{k_{GC} I_{LD}^{0.5}}{k_{GL} 31.5 f^2 \Delta I_s^{0.5}}} \quad . \tag{8}$$

At these optimal values of L weight of capacitor and reactor in one link are equal.
As example it can be shown case at I_{LD}=200 A, [ΔI_s]=0.1 A, f=1 kHz , k_{GL}=20 kg/mH, k_{GC}=5 kg/mF. For single link filter optimal L(1)= 4mH, optimal C(1)=15.6mF, which allow to install filter with total weight in 158 kg. For double link filter at same indicators $L_{opt(2)}$=0.56mH, $C_{opt(2)}$=2.28mF which allow to install filter with total weight 45.2 kg, i.e. in 3.49 times lighter.
Relation between weight of the both optimal reactors is

$$\frac{L_{opt(2)}}{L_{opt(1)}} = \sqrt[4]{\frac{\Delta I_s}{I_{LD}}} \quad . \tag{9}$$

If for instance $[\Delta I_s]$=0.1 A, as it is for railway catenaries grid of Latvia , I_{LD}=200 A then this relation is 0.149, i.e. total weight of reactors of double link filter will be in 3.5 times smaller. In same relation will be also decreasing of the total weight of filter. Effect depends on relative value of $[\Delta I_s]^* = [\Delta I_s]/I_{LD}$ where $[\Delta I_s]$ is admissible value of DC source current full range deviation:

$$\frac{W(2)}{W(1)} = 2\sqrt[4]{\Delta I^*} \quad . \tag{10}$$

This relation is graphical presented on Fig.3.

As it's seen from the picture effect in lessening of weight can be obtained only at small values of $[\Delta I]^*$. At $[\Delta I]^* \approx 0.1$ a single link filter is already more efficient.

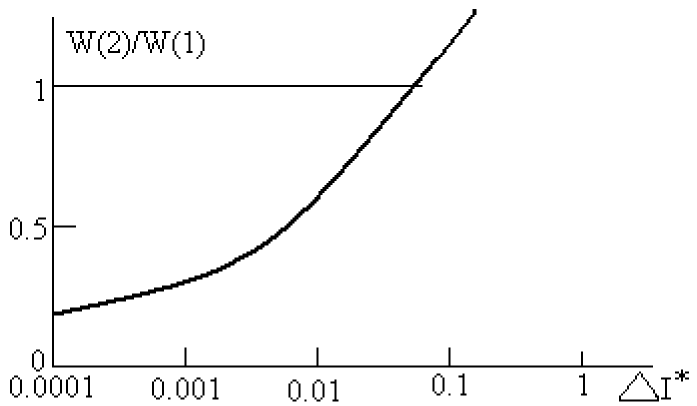


Fig.3. Relation of weights of the single and double link filters versus relative oscillation range of source current

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Parameters of filters for BOOST converter

Other case of DC PWM is BOOST converter when filter is influenced with gradually and practically linear in time rising and decreasing current i_B (Fig.4) with an averaged value $I_{LD}/(1-D)$. Also in this case in circuit of source can be introduced as single as also double link filters and can be accepted calculation method presented above.

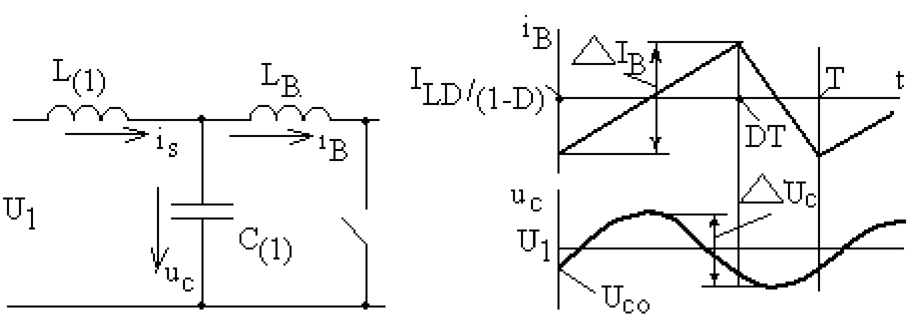

Fig.4. Scheme of installation of input filter in BOOST converter and diagrams of the filter signals

Deviation of current i_B can be described at rising part as

$$i_{Br} = \frac{I_{LD}}{1-D} - \frac{\Delta I_B}{2} + \frac{\Delta I_B \times t}{DT} \tag{11}$$

where maximal value of D≈0.8 and ΔI_B=UxDT/L. The alternating part of this current is changing voltage of the capacitor C because i_C=- $i_{B\sim}$=0.5ΔI_B - ΔI_B .t/DT. As result at rising part of i_B voltage of capacitor changes as

$$u_C = \frac{\Delta I_B t}{2C} - \frac{\Delta I_B t^2}{2CDT} + U_{C0} \tag{12}$$

where maximal value is at t=0.5DT:

$$U_{c\max} = \frac{\Delta I_B DT}{4C} - \frac{\Delta I_B DT}{8C} + U_{c0} \quad . \tag{13}$$

The minimal instantaneous value of u_c takes place at lowering part of i_B when

$$i_{Bl} = \frac{I_{LD}}{1-D} + \frac{\Delta I_B}{2} - \frac{\Delta I_B t}{(1-D)T}$$

and

$$U_{c\min} = \frac{\Delta I_B (1-D)T}{8C} - \frac{\Delta I_B (1-D)T}{4C} + U_{c0} \quad . \tag{14}$$

The full range of oscillation for capacitor's voltage

$$\Delta U_c = \frac{\Delta I_B T}{8C} = \frac{DU_1}{8f^2 L_B C} \quad . \tag{15}$$

Applying a regulation that averaged by cycle voltage u_C is equal to the voltage's value of source U_1, a value of U_{C0} is

$$U_{C0} = U_1 + \frac{\Delta I_B T}{12C}(1-2D) \quad . \tag{16}$$

Assuming a oscillations of the capacitor's voltage as sinusoidal it's possible calculate a full range of source current oscillations as

$$\Delta I_{s(1)} = \frac{DU_1}{16\pi f^3 L L_B C} \quad . \tag{17}$$

When [ΔI_s] is the admissible value of oscillation range a necessary parameters of LC filter can be find as

$$LC_{(1)B} = \frac{D_{\max} U_1}{[\Delta I_s].16\pi f^3 L_B} \quad . \tag{18}$$

Applying above mentioned method

$$L_{opt(1)B}=\sqrt{\frac{k_{GC}LC_{(1)B}}{k_{GL}}}=\sqrt{\frac{k_{GC}DU_1}{k_{GL}[\Delta I_s].16\pi f^3 L_B}} \quad . \tag{19}$$

Introducing a double link filter a found above value of $\Delta I_{s(1)}$ is oscillation range for reactor L_2 of filter and is influencing to capacitor C_1 of filter (Fig.2) creating its voltage oscillation full range

$$\Delta U_{C1}=\frac{DU_1}{32\pi^2 f^4 L_2 L_B C_2 C_1} \tag{20}$$

but this voltage deviation in its turn – a full oscillation range of the source current

$$\Delta I_{s(2)}=\frac{DU_1}{64\pi^3 f^5 L_1 L_2 L_B C_1 C_2} \quad . \tag{21}$$

Comparing the full oscillations of the both filters its relation is

$$\frac{\Delta I_{s(2)}}{\Delta I_{s(1)}}=\frac{1}{4\pi^2 f^2 L_1 C_1} \quad , \tag{22}$$

i.e. practically same as for BUCK converter.

Optimal in respect to weight a value of reactor's inductance for double link filter at $L_1=L_2=L$ and $C_1=C_2=C$ is

$$L_{opt(2)B}=\sqrt{\frac{k_{GC}(DU_1)^{0.5}}{k_{GL}[\Delta I_s]^{0.5} 8\pi^{1.5} f^{2.5} L_B{}^{0.5}}} \quad . \tag{23}$$

Relation between the optimal inductances of the both reactors is

$$\frac{L_{opt(2)B}}{L_{opt(1)B}}=\sqrt{\frac{2[\Delta I_s]^{0.5}}{\pi^{0.5}[\Delta I_B]^{0.5}}} \quad . \tag{24}$$

If for instance ΔI_B=20A, ΔI_s=0.5A then this relation is 0.42 i.e. total weight of double link filter will be 1.19 times smaller. It needs to remark that for BUCK converter maximum DC component of reactor's current is I_{LD} but for BOOST converter it is $I_{LD}/(1-D)$, i.e. for the BOOST converters a factor k_{GL} must be applied in $(1-D)^{-2}$ times bigger. It means that if D_{max}=0.7 and k_{GL} for BUCK converter is 20 kg/mH then for BOOST k_{GL}=222 kg/mH.

If for instance D_{max}=0.7 for BOOST converter , U_1=100 V, $[\Delta I_s]$=0.5 A, f=1 kHz, ΔI_B=20A then optimal inductance for single link filter is $L_{opt(1)B}$=0.134 mH, but for double link – $L_{opt(2)B}$=0.057 mH and total weight of the first mode filter will be 59.5 kg but of the second – 50.6 kg.

Effect of appliance of double link filter at BOOST converter can be improved with enlargement of applied ΔI_B , i.e. decreasing an inductance and size of BOOST reactor L_B .

CONCLUSIONS

1. Applying a double link filter in DC source circuit it's possible in DC pulse modulation system decrease a full oscillation range of source current at equal weight and size of filter as for single link filter whether otherwise.
2. Positive influence of application of double link filter is higher at smaller relation between admissible value of source current full oscillation range and load's current for BUCK converter whether BOOST reactor's current oscillation range for BOOST converter.
3. As indicator can be accepted a value of relation between source current oscillation and load's current for BUCK converter equal to 0.05. If relation is higher than weight of a double link filter is greater than of single link and opposite.

LITERATURE

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Rankis I. The double link LC filters for pulse regulation systems.
Evaluation of parameters of the double link and single link LC filters for BUCK and BOOST converters is provided. Equations for calculation of oscillation range of currents and voltages of the DC source are obtained. Also is provided evaluation of a weight of reactive elements for filters with optimal by weight parameters. Comparison of the both modes of filters shows that efficiency of weight decreasing at application of the double link filters is dependant on relation between source current oscillations range and load's current for BUCK converters and between the first and full scale oscillations of BOOST reactor's current for the second mode converters. Effect is greater at small values of these relations. For BUCK converters a threshold value of this relation is 0.05; at largest values single link filter is better. In case of BOOST converter decreasing of the relation is possible decreasing an inductance of BOOST reactor, i.e. increasing an oscillations of the reactor's current.

Raņķis I. Divpakāpju LC filtri impulsregulēšanas sistēmām .
Analizēta divpakāpju un vienpakāpes LC filtru darbība līdzsprieguma paaugstinošos un pazeminošos impulsregulatoros. Iegūtas izteiksmes strāvu un spriegumu pulsāciju aprēķināšanai ar aba tipa filtriem gan pazeminošā (BUCK), gan paaugstinošā (BOOST) pārveidotāja gadījumos. Veikts aba veida filtru parametru salīdzinājums, kā arī to svara salīdzinājums optimāli pēc svara novērtētiem abu tipu filtriem. Parādīts, ka , pielietojot divpakāpju filtrus, pie mazām attiecībā starp pieļaujamo avota strāvas pulsācijas diapazonu un slodzes strāvu BUCK pārveidotājiem un starp pirmo parametru un BOOST reactora strāvas pulsācijas diapazonu ir iespējams būtiski samazināt divpakāpju filtra svaru attiecībā pret vienpakāpes. Kā robežvērtība var tikt pieņemta attiecība 0.05; pie lielākām attiecībām divpakāpju filtrs ir smagāks par vienpakāpes.

Ранькис.И. Двухступенчатые фильтры для систем импульсного регулирования.
Произведен анализ работы однозвенного и двухзвенного фильтров в системе импульсного регулирования с понижающим и повышающим напряжение импульсным элементом. Получены выражения для расчета пульсаций тока источника постоянного тока для обеих фильтров, а также проведено сравнение эффективности сглаживания и весов обеих фильтров при оптимальном выборе параметров при минимуме весов. Показано, что применяя двухступенчатый фильтр при малых отношениях между необходимыми пульсациями токов источника и нагрузки возможно существенное снижение массы двухступенчатого фильтра по сравнению с одноступенчатым. Пороговым значением этого отношения является число 0,05; при больших соотношениях двухступенчатый фильтр тяжелее. Подобное же отношение в силе и для понижающего напряжение преобразователя, однако пульсации тока источника необходимо отности к пульсациям тока повышающего напряжение дросселя.