

Optimization of Cúk Voltage Regulator Parameters for Better Performance and Better Efficiency

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Abstract—This paper discusses the harmonic distortion and voltage-current ripple minimization of a Cúk regulator based on the design optimization of its parameters using multichannel connection with uncoupled smoothing filters. The main attention is focused on the analysis and simulation of the fundamental and two-phase parallel connection of Cúk regulator with uncoupled smoothing filters. A detailed analysis has been done to show the benefits of uncoupled smoothing filters and their positive impact on balancing the energy compensation between the capacitors and inductors of the double-phase Cúk regulator as compared to conventional one. As a result of that the dc source current values do not go from positive to negative and vice versa as in the case of a fundamental connection which does not cause any saturation problem for the regulator. In general, multichannel parallel connection of Cúk regulators with uncoupled smoothing filters has ingrained benefits such as eminent current distribution characteristics, sacredness to component tolerance, reduction of parasitic effects and relief in current control complexity. Specifically, by employing double-phase connection with uncoupled smoothing filters for these regulators, overall current fluctuation can be effectively reduced by more than 25% after introducing the double-phase connection, compared to that of simple connection. Moreover, it is proved that the output voltage ripple of the double-phase connection is also reduced by more than 25% from that of the fundamental connection. Computer simulations using Simplorer 7 or Matlab and Excel have been done to validate the concepts.

Keywords—Cúk regulator; smoothing filters; double-phase connection; overall current ripple

I. INTRODUCTION

Due to environmental problems, the development of renewable energy has received much attention. Moreover, the green-house emissions of the generation system should be reduced according to international regulations [1]. One of the alternative energy resources is fuel cells that have attracted a great deal of attention.

To improve the performance of the fuel cell system, a fuel cell DC-DC converter with an appropriate controller is needed to regulate the energy flow and automatically adjust the output voltage of the converter [2]. The Dc-Dc chopper must be highly efficient and with less ripple.

A Cúk converter is a common type of converter which is using both buck and boost circuits converter will Change the

voltage to a low or higher voltage level based on the characteristics that are designed for it [2].

Over the past few decades, the research of power electronics has focused on the development of multichannel parallel connections of DC-DC regulators in order to increase the ability of energy 2 processing and improve the reliability of the performance electronic system. The advantages of the regulator design using interlaced parallel regulators are the elimination of the ripple in both the input and output voltage and current curve waveforms to the maximum extent [3-5]. This will cause a lower value of the amplitude of the ripple and a high frequency in fluctuation in the resulting input and output waves. In addition, multichannel parallel power regulator connections reduce maintenance, increase reliability and tolerate faults. The insertion technique generally consists of shifting the control signals of several regulatory cells connected in parallel, and operating at the same switching frequency. The maximum benefits of interlacing can be achieved at a specific operating point. In general, for the Cúk regulator having one filter, the topology of one switch gives satisfactory performance in most applications, where the output voltage is greater than the input voltage but with a negative sign.

However, in a number of applications such as voltage correction circuits, energy saving and storage, and transformation of distributed power and solar systems, the performance of the Cúk regulator can be improved by implementing a Cúk with multiple channels in parallel and several smoothing filters.

The time-varying transfer function and parasitic effects of energy storage elements of a Cúk regulator leads to a positive/negative variation in the value of the source current and in a distortion in the output voltage and current. However, the current sourcing behavior of Cúk regulator helps for the use of parallel connection which can help solve previously mentioned problems and can help paralleling many PV panels on the same bus of Common Coupling [4-7].

This paper proposes a new two-phase connection topology with uncoupled smoothing filters based on Cúk regulator with two-switch two-diode connected in parallel. Multichannel Cúk regulators operating in continuous mode of the filter current have better use of power equipments and devices, increasing power efficiency, lower losses and lower overall current

fluctuations. However, in some cases, it is also acceptable that a regulator operating in a discontinuous current mode of the filter is required. For example, multi-channel DC regulators operating in a discontinuous current mode have a lower diode loss in the case of a reverse-recovery regime and a lower loss of switching on the transistor [6-9].

Moreover, the main problem of the design between parallel channels is the simultaneous distribution of currents into individual channels. It can be pointed out that if two similar but independently controlled Cúk regulators with the same input and output voltage, the regulator with 3 a larger duty cycle can operate in the continuous mode of the filter current, while the other will work in the discontinuous current mode of the filter. In these conditions, the regulator in the continuous current mode will take over any additional loading current. So, the current sharing is very sensitive to the mismatch in the duty cycle. The design of the control circuits for equal current sharing was discussed in some literature [9-12]. Conventional multi-channel Cúk regulator is typically used for applications with input current and voltage to output current and voltage conversion. An example is that the interlaced Cúk regulator is sometimes used in applications with high power to eliminate the losses of reverse – recovery of the rectifier via the control of Cúk regulators on the boundary of continuous or discontinuous current, so that the switches are switched on, When the current over the corresponding rectifier is zero. In addition, the Cúk regulator is also used in solar systems for the production of large DC voltages from PV modules.

II. SIMPLE CÚK REGULATOR

The one-channel Cúk regulator is illustrated in “Fig. 1”. The circuit model of such a regulator comprises a DC input voltage source, input filter L_1 , controllable switch S_1 , forward capacitor C_1 , diode D_1 , filter L_2 , output filter capacitor C_o and load resistance R. Its principle of operation explained in “Fig. 2” is currently known.

The Cúk voltage regulator provides an output voltage with a value smaller or larger than the input voltage value, but it is opposite to the input voltage. Its operation can be divided into two regimes: Regime 1 starts when the S_1 switch is on during the t_1 time, and its freewheeling diode is off. The current through filter L_1 raises linearly while simultaneously the C_1 capacitor voltage powering diode D_1 in the reverse direction which keeps it in the off time [17].

The C_1 capacitor is charged with energy through the circuit created by C_o , load and L_2 . Regime 2 starts with the main switch S_2 in the off regime; the diode leads the currents of the L_1 and L_2 filters, while the C_1 capacitor is charged with a current of the L_1 filter and the input power, V_s . The energy stored in the L_2 filter is now transferred to the load. The steady voltage and current curve waveforms for $1/2 \leq k \leq 1$ are shown in “Fig. 3”.

A positive property of this connection is the continuous current at the input and output of the regulator. The disadvantages of the Cúk regulator represent a large number of reactive components and high current voltage stresses on the switch, diode and capacitor C_1 and as a result of that the source current flowing through the DC source, i_s may have negative

values for a short time during $0 \leq k \leq 1/2$, as shown in “Fig. 4”.

To obtain the DC voltage transfer function, we use the principle that the average current through the capacitor is zero for steady-state operation. Suppose the L_1 and L_2 filters are large enough to allow their current fluctuation to be decreased. The C_1 capacitor is at steady state if

$$I_{L1}t_1 = I_s t_1 = I_{L2}t_2 \Rightarrow I_s DT = I_{L2} (1 - D)T \quad (1)$$

For a lossless regulator, the input power is equal to the output power

$$P_s = P_o \Rightarrow V_s I_s = -V_o I_{L2} \quad (2)$$

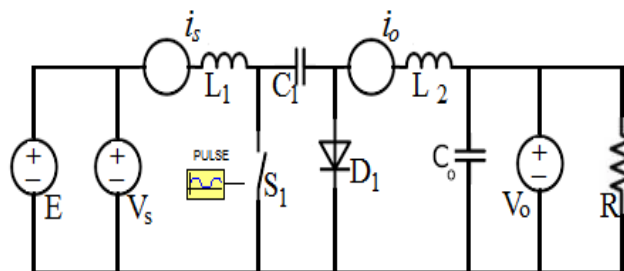


Fig. 1. Cúk Regulator Equivalent Circuit.

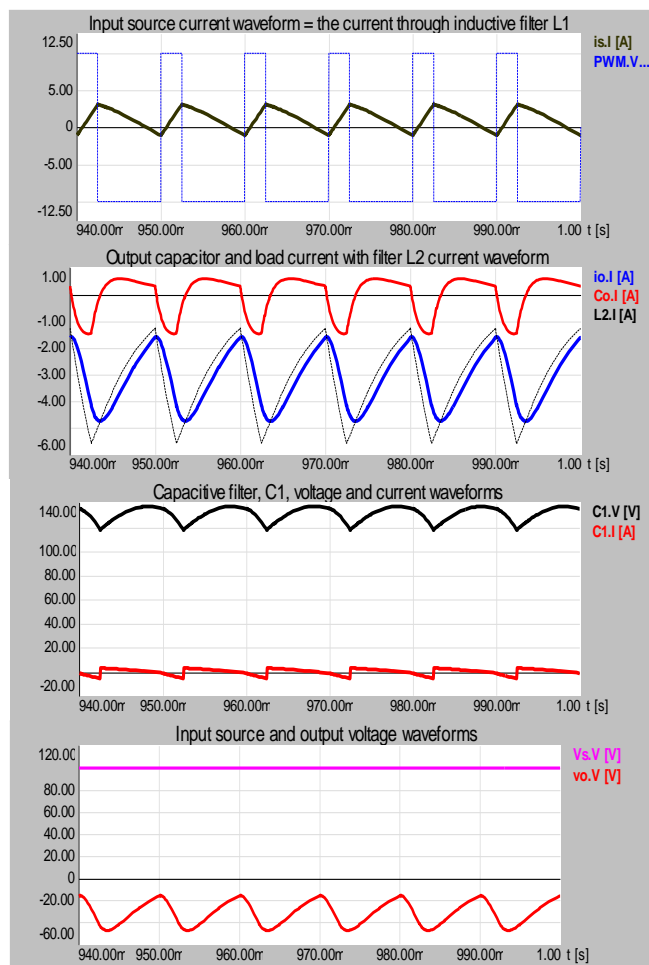


Fig. 2. Cúk Regulator with its Voltage and Current Waveforms for $0 \leq k \leq 1/2$.

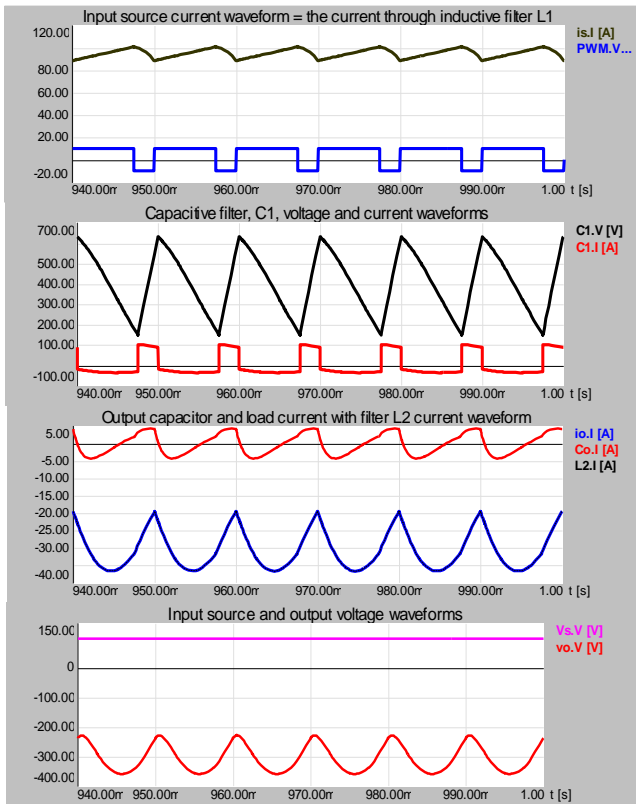


Fig. 3. Cúk Regulator with its Voltage and Current Waveforms for $1/2 \leq k \leq 1$.

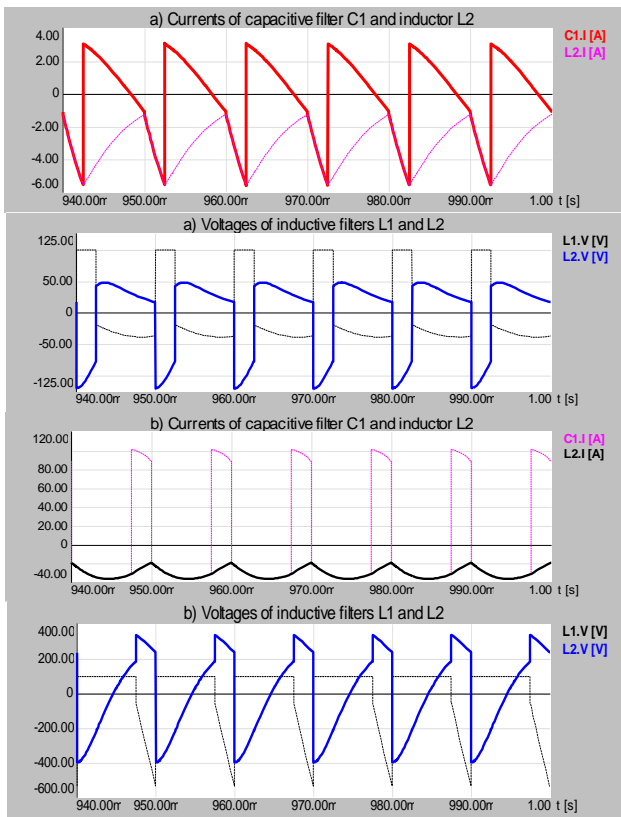


Fig. 4. Additional Waveforms of Cúk Regulator for: a) $k \leq 1/2$ and b) $1/2 \leq k \leq 1$.

Combining these two equations, the dc voltage transfer function of the Cúk regulator is

$$V_o = -\frac{k}{1-k} V_s \quad (3)$$

When transistor S_1 is off, capacitor C_1 is charged by the input current for $t = t_2$. The average charging current of capacitor C_1 is $I_{C1} = I_s$ and the peak-to-peak ripple voltage of the capacitor C_1 is:

$$\Delta V_{C1} = \frac{1}{C_1} \int_0^{t_2} I_{C1} dt = \frac{1}{C_1} \int_0^{t_2} \frac{\Delta i_s}{4} dt = \frac{\Delta i_s t_2}{4 C_1} \quad (4)$$

Substituting for $t_2 = \frac{1-k}{f}$ and for $\Delta i_s = \frac{kV_s}{fL}$, Eq. (4) becomes:

$$\Delta V_{C1} = \frac{V_s}{4f^2LC_1} k(1-k) \quad (5)$$

When the main switch is on, it carries currents of filters, L_1 and L_2 , which results in a high peak current through this transistor. And because the capacitor provides the energy transfer, the fluctuation of the capacitor C_1 current is also very high. Therefore, the peak-to-peak ripple of the currents flowing into both inductors i_1 and i_2 for a closed or open switch is:

$$\Delta i_1 = \frac{k V_s}{f L} \quad (6)$$

$$\Delta i_2 = \Delta i_o = \frac{V_{C1} - V_o}{f L} k = \frac{-V_o}{f L} (1 - k) = \frac{k V_s}{f L} \quad (7)$$

Since the peak-to-peak ripple of the load current, Δi_o , is the same as the ripple of inductor current, Δi_2 , we get for the peak-to-peak ripple of voltage ΔV_{Co} :

$$\Delta V_{Co} = \frac{1}{C_o} \int_0^{T/2} I_{Co} dt = \frac{1}{C_o} \int_0^{T/2} \frac{\Delta i_2}{4} dt = \frac{\Delta i_2}{8fC_o} = \frac{kV_s}{8f^2C_oL} \quad (8)$$

III. MULTICHANNEL CÚK REGULATOR WITH UNCOUPLED FILTERS

A circuit diagram for a Conventional two-channel connection of Cúk regulator with uncoupled filters L_1, L_2 is shown in “Fig. 5”. Such regulator has two legs connected in parallel, S_1, D_1 and S_2, D_2 . They are supplied from a dc source V_s and they are switched on at different instants of time with a time displacement of T/n (T is the operating period of each switch and n is the number of channels of the regulator). The load comprises the following elements: resistor R , uncoupled smoothing filters L_1, L_2, L_3 and L_4 , which are inactive electric components created from a wire coil wound around an eliminated magnetic core to have their magnetic flux within all turns of the coil winding. The magnetic field generated from them is much stronger than the one generated by the single smoothing filter coil due to the induced voltage produced at their terminals as a result of the current flowing into both of them.

The current in filter L_1 is assumed to increase during its on-time, i_1 linearly from $I_{1,a}$ to $I_{1,b}$. During the off-time of switch S_1 and on-time of D_1 , the forward capacitor C_1 is discharging and therefore, current i_1 decreases linearly from $I_{1,b}$ to $I_{1,a}$, and:

$$V_s - V_{C1} = L \frac{\Delta i_1}{t_2} \Rightarrow t_2 = L \frac{\Delta i_1}{V_s - V_{C1}} \quad (9)$$

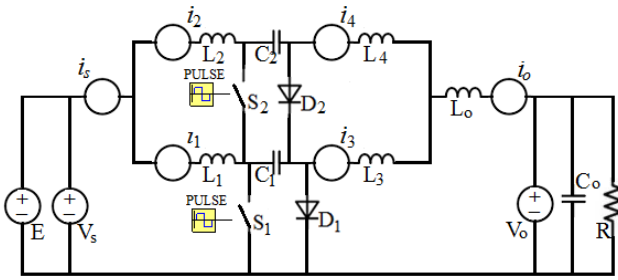


Fig. 5. Conventional Cúk Regulator with uncoupled Filters.

The peak-to-peak ripple of the phase current, Δi_1 under steady-state conditions should be same whether the switch is on or off, and it is obtained for the whole operating period of the regulator, T , as shown in “Fig. 6”.

Peak-to-peak ripple in regime of $1/2 \leq k \leq 1$

Traditionally, the multichannel Cúk regulator having smoothing filters magnetically uncoupled perfectly decreases the overall voltage-current peak-to-peak ripples at the input and output of the regulator. It also significantly improves as said before the power efficiency as compared to the basic connection of Cúk regulator and helps improving the balance of energy transfer between energy storage elements. Therefore, the regulator never gets into a saturation problem and its dc input current never goes from positive to negative values. These investigations are recorded for typical and linear design conditions of the filters, whereas $L_1 = L_2 = L_3 = L_4 = L$. Therefore, the averaged values of currents into both channels are divided between filters, L_1, L_2 equally by regulating the duty cycle of every switch in each leg with a time displacement of $T/2$ [17-19].

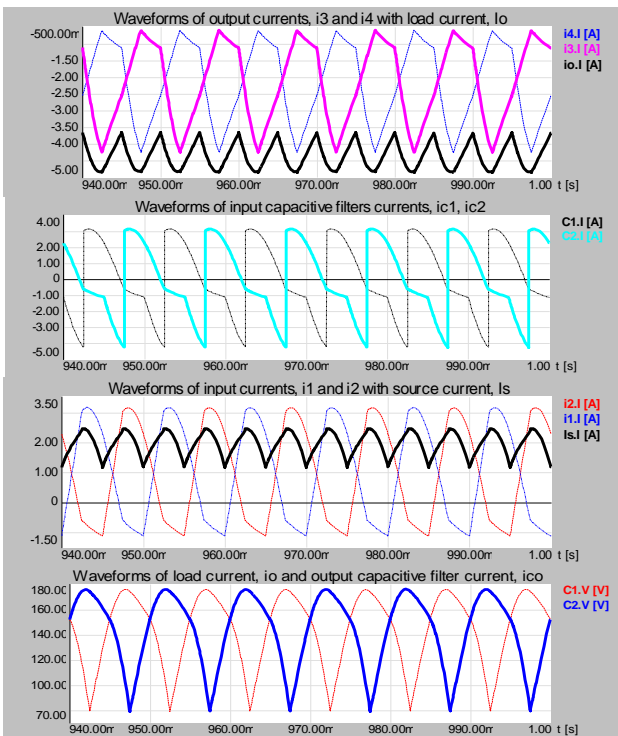


Fig. 6. Current and Voltage Steady state Waveforms of Two-Channel Connection of Cúk Regulator for $0 \leq k \leq 1/2$.

Same currents but with opposite directions are flowing into filters, L_3 and L_4 . So, considering a continuous operating mode of conduction, then the mathematical model representing the system when S_1 is switched on, for a time t_1 is as follows:

$$V_s = L \frac{I_{La} - I_{Lb}}{t_1} \Rightarrow t_1 = L \frac{\Delta i_1}{V_s} \Rightarrow \Delta i_1 = \frac{k V_s}{f L} \quad (9)$$

The current in filter L_1 is assumed to increase during its on-time, t_1 linearly from I_{La} to I_{Lb} . During the off-time of switch S_1 and on-time of D_1 , the forward capacitor C_1 is discharging and therefore, current i_1 decreases linearly from I_{Lb} to I_{La} , and:

$$V_s - V_{C1} = L \frac{\Delta i_1}{t_2} \Rightarrow t_2 = L \frac{\Delta i_1}{V_s - V_{C1}} \quad (10)$$

The peak-to-peak ripple of the phase current, Δi_1 under steady state conditions should be same whether the switch is on or off, and it is obtained for the whole operating period of the regulator, T , as follows:

$$T = t_1 + t_2 = L \frac{\Delta i_1}{V_s} + L \frac{\Delta i_1}{V_s - V_{C1}} \Rightarrow \Delta i_1 = \frac{V_s (V_s - V_{C1})}{f L (2V_s - V_{C1})} \quad (11)$$

The averaged voltage across capacitor C_1, V_{C1} is obtained from the equality of the fluctuation in the on and off-time as follows:

$$\Delta i_1 = \frac{V_s}{L} t_1 = \frac{V_s}{L} k T = \frac{V_s - V_{C1}}{L} t_2 = \frac{V_s - V_{C1}}{L} (1 - k) T \Rightarrow V_{C1} = \frac{(1 - 2k)}{(1 - k)} V_s \quad (12)$$

Similar thoughts may be applied for the second channel current, i_2 . Therefore, because the smoothing filters $L_1 = L_2 = L$ are identical, the peak-to-peak ripple of the regulator input current i_s may be determined for $0 \leq k \leq 1/2$ as shown in “Fig. 7”, when one main switch is on and the other is off as follows:

$$\Delta i_s = \frac{V_s}{L} t_1 - \frac{V_s - V_{C1}}{L} t_1 \Rightarrow \Delta i_s = \frac{V_{C1}}{f L} k = \frac{k(1 - 2k)}{(1 - k) f L} V_s \quad (13)$$

Concerning Δi_s in the region of $1/2 \leq k \leq 1$ as shown in “Fig. 7” when both switches are on, it may be obtained as follows:

$$\Delta i_s = 2 \frac{V_s}{L} (t_1 - \frac{T}{2}) \Rightarrow \Delta i_s = \frac{(2k - 1)}{f L} V_s \quad (14)$$

Concerning the output currents, i_3 and i_4 through filters, L_3 and L_4 , let's assume that current i_4 increases linearly in time t_1 :

$$V_{C1} - V_o = L_4 \frac{\Delta i_4}{t_1} \Rightarrow t_1 = L \frac{\Delta i_4}{V_{C1} - V_o} \quad (15)$$

And in time t_2 :

$$V_o = -L_4 \frac{\Delta i_4}{t_2} \Rightarrow t_2 = -L \frac{\Delta i_4}{V_o} \quad (16)$$

Combining 14 and 15:

$$T = t_1 + t_2 \Rightarrow \Delta i_4 = \frac{V_o (V_{C1} - V_o)}{f L (2V_o - V_{C1})} = \frac{V_s}{f L} k \quad (17)$$

Equating the input power to the output power for a lossless regulator and Eq. (16) to Eq. (17), we get for the output voltage and current:

$$V_o = -\frac{kV_s}{1-k}, \quad I_o = \frac{1-k}{k} I_s \quad (18)$$

The fluctuation of load current i_o may be determined for $0 \leq k \leq 1/2$ when one main switch is on and the other is off as:

$$\Delta i_o = \frac{V_{c1}-V_o}{L} t_1 + \frac{V_o}{L} t_1 \Rightarrow \Delta i_o = \frac{V_{c1}}{fL} k = \frac{(1-2k)kV_s}{(1-k)fL} \quad (19)$$

When both switches are on, $\Delta i_o \Delta i_o$ may be obtained for $1/2 > k > 1$ as:

$$\Delta i_o = 2 \frac{V_{c1}-V_o}{L} (t_1 - \frac{T}{2}) \Rightarrow \Delta i_o = \frac{(2k-1)}{fL} (V_{c1} - V_o) = \frac{(2k-1)}{fL} V_s \quad (20)$$

The average value of capacitor C_o current, which flows for $T/2$, is $I_{co} = \Delta i_o/4$ and therefore, the peak-to-peak ripple voltage of capacitor C_o is:

$$\Delta v_{co} = \frac{1}{C_o} \int_0^{T/2} I_{co} dt = \frac{1}{C_o} \int_0^{T/2} \frac{\Delta i_o}{4} dt = \frac{\Delta i_o}{8fC_o} \quad (21)$$

Concerning the fluctuation of the voltage on capacitors, C_1 , or C_2 is:

$$\Delta v_{c1} = \frac{1}{C_1} \int_0^{t_2} I_{c1} dt = \frac{1}{C_1} \int_0^{t_2} \frac{\Delta i_1}{4} dt = \frac{\Delta i_1}{4fC_1} (1-k) \quad (22)$$

The peak-to-peak ripple, in this case, has the same value as that for the fundamental connection estimated in Eq. (5).

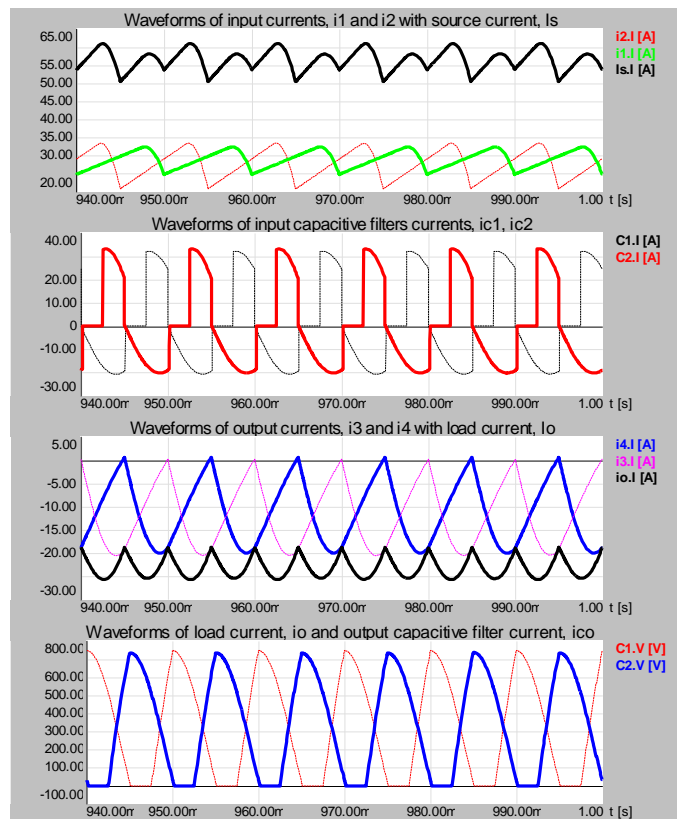


Fig. 7. Cúk Regulator with its Voltage and Current Waveforms for $1/2 \leq k \leq 1$.

The current and voltage fluctuations are undesired behavior which should be improved since they adversely affect the losses and heating effects in the system load above the acceptable limits and consequently decreases the expected life of the battery in which the energy created by PV systems is stored. It also makes the regulation of the regulator worse since it generates a distortion not only in the current and voltage waves at the output of the regulator but also at its input which requires further control processors and makes its control more sophisticated and the dynamic behavior of the PV supply system unstable and less efficient [13-16].

IV. SIMULATION RESULTS

The peak-to-peak ripple of source and load current of the Cúk regulator with fundamental connection and double-phase connection with smoothing chokes is illustrated using previously derived equations as a function of duty time ratio, k , in “Fig. 8”. The regulator simulation parameters for the current continuous regime are listed in “Table I” as [20-22].

The ripple of currents, i_s and i_o is directly proportional to the supply voltage V_s and inversely proportional to the chopping frequency of the regulator f and the filter inductance value L .

From “Fig. 8” and “Fig. 9” it is clear that the peak-to-peak source and load current ripple of double-phase connection of Cúk regulator with smoothing filters has smaller values than that for its fundamental connection. It should be mentioned that the number of smoothing filters for n-channel connections is n filters, but compared to the basic connection, each filter is designed to the value of $1/n$ of the source current.

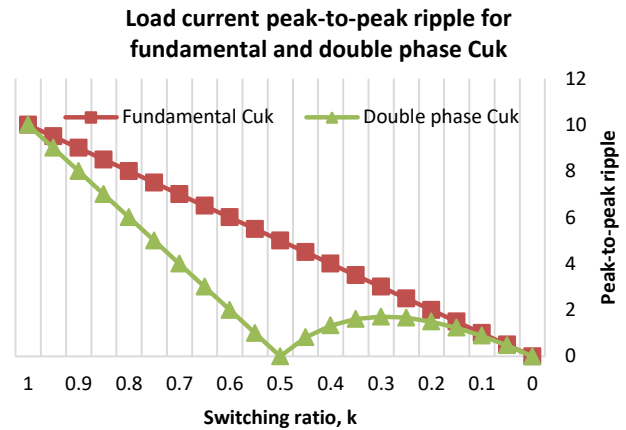


Fig. 8. Peak-to-Peak Ripple of Load Current Δi_o Versus Duty Ratio k .

TABLE. I. TECHNICAL PARAMETERS OF THE SIMULATED REGULATOR

Parameter	Symbol	Real value
Smoothing filters:	$L_1=L_2= L_3=L_4$	10mH
Regulator operating period:	T	10ms
Supply voltage	V_s	100V
Load resistance:	R	10 Ω
Input capacitive filter	$C_1=C_2$	100 μ F
Output capacitive filter	C_o	100 μ F

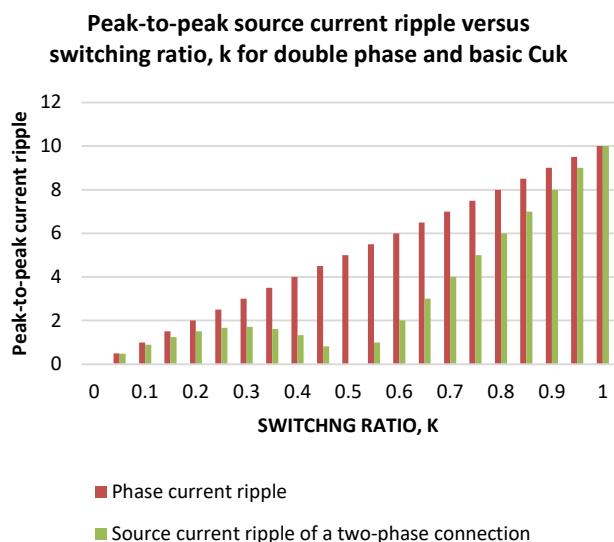


Fig. 9. Peak-to-Peak Ripple of Source Δi_s versus Duty Ratio k .

In addition, “Fig. 10” shows that with an increase in switching frequency, current fluctuations in the two-channel connection are dramatically reduced compared to the underlying fundamental connection. The advantages of reducing fluctuations in the current waves due to multichannel connection of Cúk regulator result in the use of smaller filters and capacitors on the output and input of the regulator for the same requirements for the total peak-to-peak current and voltage ripple. Even the transient ripple of output voltage on the C_1 and C_2 channel capacitors can also be reduced due to smaller output coils, resulting in the use of smaller output capacitors. While the ripple on the channel capacitive filters, C_1 and C_2 does not change as shown in “Fig. 11” in blue, it is dramatically decreased on the output capacitive filter, C_o for double-phase connection (in green) as compared to that of the fundamental connection in red [9, 21-24].

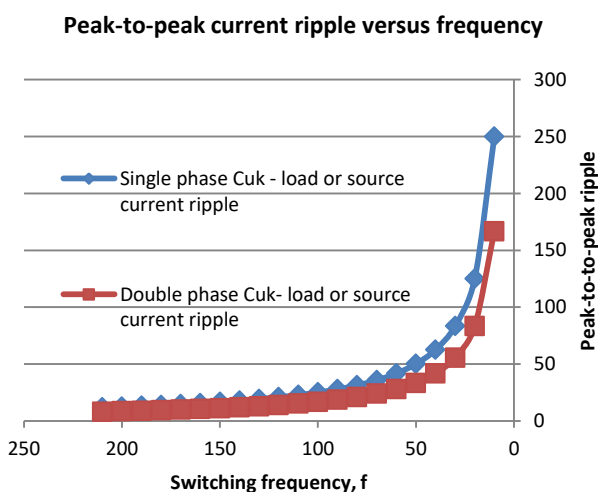


Fig. 10. Peak-to-Peak Ripple of Input forward and Output Capacitive Filter Voltages Versus Switching Ratio k .

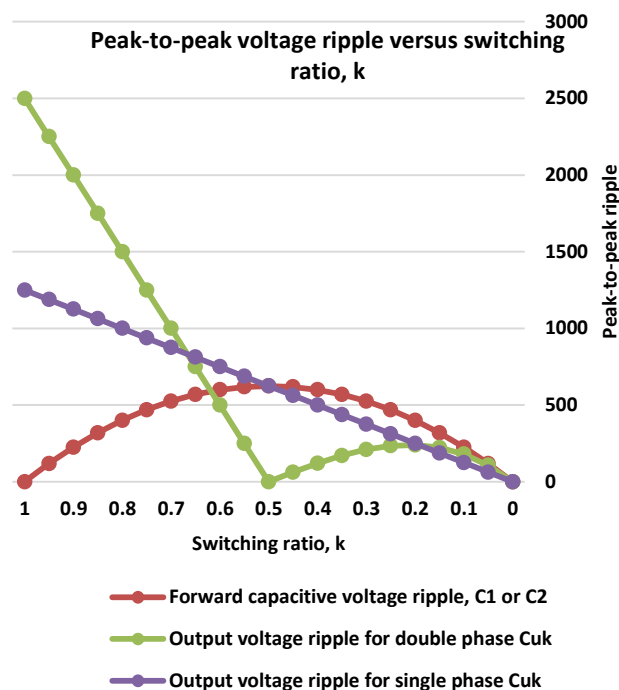


Fig. 11. Peak-to-Peak Ripple of Input forward and Output Capacitive Filter Voltages Versus Switching Ratio k for Both Topologies of Cúk.

V. CONCLUSION

This paper focuses on the concept of total reduction of current and voltage ripple of the Cúk regulator using multichannel parallel connection with disconnected smoothing filters. A detailed analysis was performed, while simulations and experimental results were performed to verify the concept. In addition, it was found that the fluctuations in the channel currents will also be reduced compared to the basic connection of the regulator. This can increase efficiency and improve the system's dynamic performance. Furthermore, in the case of a single-phase Cúk regulator, the switching ratio should be carefully selected to achieve better results and to avoid parasitic effects of the capacitive and inductive filters. This is not a problem of the double-phase Cúk regulator with smoothing inductive filters that help to solve the parasitic effect of capacitive filters on the planar inductive filters.

- The simulations and experimental results obtained in this article lead to the following conclusion: Single-phase Cúk regulator may be given a priority when it is used for low power applications, for example, in telecom power supplies, smart home grid systems, and computer motherboards and power supplies where the parallel connection is not required.
- Two-phase connection with magnetically uncoupled/coupled filters is more favorable with respect to the present trend of high switching frequency, f , and better dynamic performance power electronic devices. These features of Cúk regulator results in a decrease of the demands to the material of smoothing inductive and capacitive filters used with it.

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