Analysis, Design, and Implementation of a Soft-Switched Active-Clamped Forward Converter with a Current-Doubler Rectifier

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Abstract

This study examines the zero-voltage switching (ZVS) operation of an active-clamped forward converter (ACFC) with a current-doubler rectifier (CDR). The ZVS condition can be obtained with a much smaller leakage inductance compared to that of a conventional ACFC. Because of the significantly reduced leakage inductance, the design is optimized and the circulating loss is reduced. The operation of ACFC with CDR is analyzed, and a detailed ZVS analysis is conducted on the basis of steady-state analysis. From the result, a design consideration for ZVS improvement is presented. Loss analysis of the converters shows that enhanced soft-switching contributes to efficiency improvement under light-load conditions. Experimental results from a 100-W (5-V/20-A) prototype verify that the ACFC with CDR can attain ZVS across an extended load range of loads and achieve higher efficiency than ACFCs.

Key words: Active-clamp circuit, Current-doubler rectifier, Forward converter, Zero-voltage switching

I. INTRODUCTION

The forward converter has been one of the most extensively used topologies in low- and mid-power DC-DC converter applications (e.g., computer and telecommunication systems) because of its simple circuitry, low cost, and high efficiency. However, several issues remain such as high-voltage spikes across the MOSFET and resetting the transformer. To solve these problems, forward converters have used several reset schemes. An active-clamp circuit is most widely used because it does not require an additional reset winding or energy dissipative component to minimize the voltage stress across the MOSFET [1]-[7]. In addition, an active-clamp circuit enables zero-voltage switching (ZVS) in a MOSFET.

In a conventional active-clamped forward converter (ACFC), the main switch can achieve ZVS by harnessing either magnetizing inductance [8]-[10] or leakage inductance [12]-[14]. Magnetizing inductance requires a gap in the transformer that increases the magnetizing current, discharging the output capacitor of the MOSFET and resulting in ZVS.

When a decreased switching loss cannot compensate for the increased conduction loss, a hard-switching operation is employed rather than a soft-switching one [10]. Consequently, this method is only suitable for converters with small input current and a high-input voltage [11]. The method of leakage inductance uses the resonance between the leakage inductance and the output capacitor of the MOSFET to discharge the stored energy. The ZVS condition is more easily met as the leakage inductance increases; however, large duty cycle losses result in an overall decrease in efficiency. Several methods have been proposed to improve ZVS operation while using a relatively large magnetizing inductance and a small leakage inductance [15]-[17]. However, these methods either require additional components [15], [16] or only apply to ACFCs with an externally driven synchronous rectifier on the secondary side [17].

In order to overcome these limitations, this paper proposes an ACFC with CDR to improve ZVS operation. CDR is widely used in applications with low-output voltage and high-output current because the root-mean-square (RMS) current on the transformer secondary is small, and the output voltage ripple is reduced [18]-[20]. Many previous studies have reported on the general advantages of CDR-based topologies [21]-[25]. It has also been reported that CDR improves ZVS operation when used with a phase-shifted full-bridge converter [26], [27]. For a
phase shifted full bridge converter, however, the primary current should decay rapidly during the zero state [27], and the output inductor current should become negative at switching instant for ZVS improvement, which compromises the general advantages of CDR. While an ACFC with CDR can inherently use the output inductor energy to improve ZVS operation, it has never been remarked before. Hence an excessive resonant inductor has been used [12] or ZVS has been reported with only empirical results [21], [28]-[30].

Therefore, the present study rigorously analyzes an ACFC with CDR to harness enhanced ZVS operation. This paper demonstrates that an ACFC with CDR improves ZVS performance and presents a design consideration for further improvements. A quantitative comparison of losses in an ACFC with CDR and those in ACFCs verifies that enhanced ZVS performance is responsible for the improvement in efficiency. The results show that enhanced soft-switching contributes to the improvement in efficiency under light-load; therefore, an ACFC with CDR exhibits high efficiency across all load conditions.

Despite its advantages, the proposed converter needs an additional output inductor. If discrete magnetic components are used, three cores are required: one for the transformer and two for the output inductors. These can increase the cost and size of the converter. However, as previous literature [31] has reported that the three cores can be replaced by integrated magnetic structures, the present study focuses on the aspect of CDR efficiency.

The paper is structured as follows: Section II describes the circuit configuration of the ACFC with CDR. Section III presents the ZVS analysis based on steady-state analysis and provides design consideration for ZVS improvement. Section IV presents loss analysis to verify the role of the enhanced ZVS performance in improving efficiency. Section V verifies the assertion of Section IV experimentally using a 100-W (5-V/20-A) prototype, and Section VI concludes the paper.

II. CIRCUIT CONFIGURATION

The circuit configurations of a conventional ACFC and an ACFC with CDR are shown in Figs. 1(a) and 1(b), respectively. Unlike the conventional ACFC, \( R_{C1} \), \( R_{C2} \), and \( R_f \) which is the equivalent series resistance (ESR) of \( L_1 \), \( L_2 \), and transformer, respectively, are considered in the Fig. 1(b) for the ZVS analysis as explained later. The auxiliary switch \( S_1 \) and clamp capacitor \( C_c \) are components of the active-clamp circuit and recycle leakage energy. The transformer is modeled with a magnetizing inductance \( L_m \) and an equivalent leakage inductance reflected on the primary side \( L_{ck} \). The main switch \( S_1 \) is operated with the duty cycle \( D \), and the auxiliary switch \( S_2 \) is operated complementary to the duty cycle of \( S_1 \) with dead times preceding and following the auxiliary switch action. Both switches include body diodes \( D_{a1} \) and \( D_{a2} \), and output capacitors \( C_{o1} \) and \( C_{o2} \). The secondary side comprises two synchronous switches \( S_{R1} \) and \( S_{R2} \); two output inductors \( L_1 \) and \( L_2 \); and an output capacitor \( C_o \).

The active-clamp circuitry can be applied to either the high side or the low side. High-side clamps are applied across the primary side of the transformer and use an N-channel auxiliary switch on the clamp network; they are appropriate for high-input-voltage applications. However, additional high-side gate circuitry is needed to drive the auxiliary switch. A low-side clamp is applied across the drain-to-source of the main switch and uses a P-channel auxiliary switch on the clamp network. The drain-to-source voltage rating of a P-channel switch is lower than that of an N-channel switch and cannot be used for off-line applications. However, it does not require any additional gate drive circuitry and improves the precision of control over the delay timing for ZVS.

The level of the input voltage in most forward converter applications is lower than the line voltage; therefore, the low-side clamp is adopted in this paper. The fundamental principles are exactly the same for both clamps; therefore, the following analyses can also be applied to high-side clamps.

III. ZVS ANALYSIS

ZVS operation of \( S_1 \) is guaranteed regardless of load variations [15]; it does not need to be considered separately in
A. Steady-state analysis

The steady-state waveforms of the ACFC with CDR are shown in Fig. 2. The operation modes and analyses are complicated by resonant operation. The circuit operation and ZVS analysis are simplified by the following assumptions:

1) Dead times are much shorter than switch turn-on times and are negligible;
2) \( L_a \) is much less than \( L_m \);
3) \( C_r \) is sufficiently large so that the clamp voltage is constant.

Since the assumptions make scarcely any changes on the minimum value of \( i_{Lk}(t) \) which is the most significant value for the ZVS analysis, they simplify the analysis without introducing any inaccuracy.

When the above conditions are applied, the total number of intervals in one switching cycle decreases from ten to two and \( D \) becomes equal to the effective duty \( D_{\text{eff}} \). Equivalent circuits for these two states are depicted in Fig. 3. The steady-state waveforms of the converter are shown in Fig. 4.

To ensure the ZVS of \( S_1 \), the energy stored in \( L_{ik} \) must be larger than the energy stored in \( C_{s1} \) at the moment at which the switch is turned on, \( t_1 \). \( L_{ik} \) and \( i_{Lk}(t_1) \) are critical determinants of the ZVS of \( S_1 \); ZVS is more easily achieved as both determinants increase. Large values of \( L_{ik} \) degrade the converter efficiency and affect the voltage conversion ratio of the forward converter. Therefore, it is more desirable to increase \( i_{Lk}(t_1) \).

In the conventional ACFC, the leakage current \( i_{Lk}(t) \) is equal to the magnetizing current \( i_{Lm}(t) \), and it discharges \( C_{s1} \) at \( t_1 \), as shown in Fig. 5(a). The ZVS operation of \( S_1 \) is not easily achieved with a small leakage inductance because the magnitude of \( i_{Lk}(t) \) is not large enough to totally discharge...
\[ I_{Lm} = \frac{R_{e1} + DR}{R_{e1} + R_{e2}} \frac{I_{o}}{N} \]  
(1)

\[ I_{L1} = \frac{R_{e2} + DR}{R_{e1} + R_{e2} + R_{e}} I_{o} \]  
(2)

\[ I_{L2} = \frac{R_{e1} + DR}{R_{e1} + R_{e2} + R_{e}} I_{o} \]  
(3)

\[ V_{C\ell} = \frac{1}{D} V_{s} \]  
(4)

\[ |i_{Lm}(t)| = \left( \frac{V_{C\ell} - V_{o} - V_{SR}}{N} \right) DT_{s} + \left( \frac{V_{C\ell} - V_{o}}{2L_{m}} \right) DT_{s}, \]  
(5)

where \( V_{SR} \) stands for the sum of voltage drops across ESRs and synchronous switches.

In the case of the conventional ACFC, \( |i_{Lm}(t)| \), which corresponds to \( |i_{Lm}(t)| \), can be written as follow [3]:

\[ |i_{Lm}(t_{1})| = \frac{E_{h} - E_{o}}{(V_{C\ell} - V_{o})} DT_{s} + \frac{E_{o}}{2L_{m}}. \]  
(6)

where

\[ E_{c\ell} = \frac{1}{2} (C_{o} + C_{s}) \left( \frac{D}{D} V_{s} \right)^{2} \]  
and \[ E_{h} = \frac{1}{2} L_{m} \left( \frac{I}{N} \right)^{2}. \]  
(7)

**B. ZVS advantageous area**

For improved ZVS operation in the ACFC with CDR relative to the conventional ACFC, \( |i_{Lm}(t)| \) has to be larger than \( |i_{Lm}(t_{1})| \). If we assume that \( E_{c\ell} = 0 \) for the worst case design and neglect \( V_{SR} \) in Eq. (5), the ZVS condition for extended load range can be described as follow:
The ACFC with CDR attains DTs.\(\rightarrow\)e loss (ad dependent for an P8ng PLN L LN C C V

\[ \frac{D^2 V_g^2 T_s^2}{L_2 I_s^2} \geq L_{\text{m}}. \] (8)

When the condition in Eq. (8) is met, the ACFC with CDR shows enhanced ZVS characteristics compared with the conventional ACFC. From small values of \(L_{\text{m}}\), the duty cycle loss is reduced and design of a forward converter becomes convenient. If the condition in Eq. (8) can be easily satisfied an ACFC with CDR represents an appropriate substitute for the conventional ACFC.

ZVS advantageous conditions for the ACFC with CDR and the conventional ACFC are investigated according to Eq. (8) for the converter system specifications given in Table I. The results for both converters are given in Fig. 6. The boundary condition line separates the region where the ACFC with CDR most easily achieves ZVS from the corresponding region for conventional ACFC. The ACFC with CDR attains ZVS with a smaller leakage inductance than the conventional ACFC. Moreover, the difference between the minimum inductances for each converter increases as the load decreases.

C. ZVS condition for ACFC with CDR

The main switch ZVS condition for the ACFC with CDR is given by the following:

\[ \frac{1}{2} V_{g} \left( \frac{d_{t}}{d_{t}} \right)^2 = \frac{1}{2} \left( C_{1} + C_{2} \right) V_{\text{m}}. \] (9)

where \(V_{\text{m}}\) is maximum input voltage.

Using Eqs. (4) and (5) while assuming that \(V_{g}\) is negligible, Eq. (9) can be arranged as

\[ L_{\text{m}} \geq \frac{C_{c}}{D_{\text{m}} \left( I_{g}^2 + L_{2}^2 N_{g}^2 \right)^2 \left[ D_{\text{m}} T_{s} \right]}. \] (10)

where \(D_{\text{m}}\) is the minimum duty ratio.

The leakage inductor for ZVS is not load dependent for an ACFC with CDR, in contrast to a conventional ACFC. A leakage inductor that meets the condition in Eq. (10) guarantees a ZVS condition across the entire range of loads. Furthermore, the ACFC with CDR can achieve ZVS while maintaining \(L_{\text{m}}\) much lesser than \(L_{\text{m}}\) if the output inductor is properly designed. The leakage inductance for ZVS is shown in Fig. 7 for particular conditions: \(L_{\text{m}}\) varies from 0 to 400 \(\mu\)H, \(L_{2}\) varies from 0.5 to 2 \(\mu\)H, and \(V_{g}\) is fixed at 48 V. The optimal design condition can be easily identified from Fig. 7.

IV. LOSS ANALYSIS

To verify that enhanced ZVS performance was responsible for improved efficiency, a loss analysis was conducted. The ACFC with CDR was designed according to the system specifications in Table I, and the results are shown in Table II. For the conventional ACFC, the design specifications are the same as those of the ACFC with CDR, except that a 1-\(\mu\)H output inductor is used in the conventional ACFC.

Loss factors considered in this analysis are as follows: 1) conduction loss in FETs and ESRs (\(P_{\text{cond}}\)); 2) switching loss in FETs (\(P_{\text{sw}}\)); and 3) transformer core loss (\(P_{\text{core}}\)). The numerical expressions for each loss factor are derived below.

First, the conduction loss is calculated from the resistance and RMS current through each resistor. The conduction loss is expressed as

\[ P_{\text{cond}} = R_{\text{diss}(S_{1})} I_{\text{rms}(S_{1})}^2 + R_{\text{diss}(S_{2})} I_{\text{rms}(S_{2})}^2 + R_{\text{diss}(SR_{1})} I_{\text{rms}(SR_{1})}^2 + R_{\text{diss}(SR_{2})} I_{\text{rms}(SR_{2})}^2 + \sum R_{\text{ESR}} I_{\text{rms}(ESR)}^2 \] (11)

where \(R_{\text{diss}}\) is the dissipation resistance of the FETs and ESRs, \(I_{\text{rms}}\) is the RMS current through each resistor, and \(P_{\text{cond}}\) is the total conduction loss.

| TABLE II |
|-----------------|----------------|
| Clamp capacitor (\(C_{c}\)) | 47nF |
| Output capacitor (\(C_{o}\)) | 47\(\mu\)F |
| Output Inductor (\(L_{1} \& L_{2}\)) | 1\(\mu\)H |
| ESR of Output Inductor (\(R_{1} \& R_{2}\)) | 2m\(\Omega\) |
| ESR of Transformer-Secondary (\(R_{s}\)) | 10n\(\Omega\) |
| Transformer turn ratio (\(N\)) | 4:1 |
| Magnetizing inductance (\(L_{m}\)) | 200\(\mu\)H |
| Leakage inductance (\(L_{\text{m}}\)) | 3\(\mu\)H |
| Main switch (\(S_{1}\)) | STP30NF20 |
| Auxiliary switch (\(S_{2}\)) | FQP12P20 |
| Synchronous Switches (\(SR_{1} \& SR_{2}\)) | IPP040N06N |
Next, the switching loss is estimated from the output capacitor loss and the power loss during the switching transition period. The switching loss can be expressed as

\[ P_{sw} = \sum_i P_{sw(S_i)} + \sum_i P_{sw(SR_i)} \]  

(12)

where \( V_i \) and \( I_i \) are the switch voltage and current, and \( t_{on} \) and \( t_{off} \).

\[ P_{sw(S_i)} = \frac{1}{2} C_i V_i^2 + \frac{1}{2} V_i I_i (t_{on} + t_{off}) f_{sw} \]  

(13)

\[ P_{sw(SR_i)} = \frac{1}{2} V_i I_{i\text{off}} f_{sw} \]  

(14)

Fig. 8. Comparison of estimated efficiency and loss components. (a) ACFC with CDR and hard-switching ACFC. (b) ACFC with CDR and soft-switching ACFCs.
and \( t_{\text{off}} \) are the turn-on and turn-off switching periods of the corresponding power MOSFET, respectively. In case of synchronous switches, only turn-off losses are accounted for because they always attain ZVS by load current and turn-on losses are negligible.

Finally, the core loss is given by

\[
P_{\text{core}} = \rho_m V_c K_c f_m B_m^\beta
\]  

(15)

where \( \rho_m \), \( V_c \), and \( B_m \) are the core material density, the core volume, and the maximum flux density, respectively. \( K_c \), \( \alpha \), and \( \beta \) are constants that can be determined by fitting the core data provided by the manufacturer [35].

The total efficiency and each loss component are calculated for four converters:

1) ACFC with CDR (\( L_m = 200 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \));
2) Hard switching ACFC (\( L_m = 200 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \));
3) \( L_{\text{ff}} \)-ZVS ACFC (\( L_m = 80 \mu \text{H} \) & \( L_{\text{ff}} = 5 \mu \text{H} \));
4) \( L_m \)-ZVS ACFC (\( L_m = 40 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \)).

Each device parameter needed in the loss calculation is obtained from the datasheet provided by the manufacturer. The results of loss analysis are shown in Fig. 8.

In Fig. 8(a), the estimated efficiency and loss components of the ACFC with CDR and hard-switching ACFC are presented. The ACFC with CDR has the lowest switching loss due to its outstanding ZVS characteristics; it exhibits a higher efficiency than hard-switching ACFC at light-load conditions, when switching losses dominate. For its small RMS current on secondary, the ACFC with CDR also exhibits higher efficiency at heavy-load range. Therefore, the ACFC with CDR achieves a high efficiency compared to the hard-switching ACFC throughout the whole load.

In Fig. 8(b), comparison of the ACFC with CDR and two soft-switching ACFCs is presented. \( L_{\text{ff}} \)-ZVS ACFC has the advantage of soft-switching due to its large leakage inductance, thereby attains ZVS from medium-load conditions. However, the duty cycle loss and auxiliary switch turn-off loss increase with the load. Consequently, the \( L_{\text{ff}} \)-ZVS ACFC exhibits the worst heavy-load efficiency of all converters. \( L_m \)-ZVS ACFC achieves soft-switching by reduced \( L_m \) and shows high efficiency at light-load conditions. However, heavy-load efficiency is worse than ACFC with CDR because of the increased conduction loss on primary side.

The loss analysis shows that the ACFC with CDR exhibits the most outstanding ZVS performance. Light-load efficiency is expected to improve with soft-switching. At heavy loads, the advantage of a small RMS current on secondary contributes to high efficiency. Two soft-switching ACFCs also show high efficiency at light-load, but heavy-load efficiency get worse because of the duty cycle loss, switch turn-off loss and primary side conduction loss.

V. EXPERIMENTAL RESULTS

The improved efficiency of the ACFC with CDR was experimentally verified. Prototypes of an ACFC with CDR (\( L_m = 200 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \)), a hard-switching ACFC (\( L_m = 200 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \)), a \( L_{\text{ff}} \)-ZVS ACFC (\( L_m = 80 \mu \text{H} \) & \( L_{\text{ff}} = 5 \mu \text{H} \)), and \( L_m \)-ZVS ACFC (\( L_m = 40 \mu \text{H} \) & \( L_{\text{ff}} = 3 \mu \text{H} \)) were built and tested.

The waveforms for the leakage inductor current (\( i_{L1} \)), transformer secondary current (\( i_{2s} \)), magnetizing inductor current (\( i_{\text{in}} \)), and two output inductor currents (\( i_{L1} \) and \( i_{L2} \)) are shown in Fig. 9 for the ACFC with CDR at 10% load. The function for \( i_{\text{in}} \) is calculated from \( i_{L1} \) and \( i_{2s} \) divided by the transformer turn ratio. As seen in Fig. 9, the average value \( <i_{\text{in}}\> \) is 226 mA, whereas the average \( <i_{L2}\> \) is 982 mA; this is nearly \( N \) times larger than \( <i_{L1} \>). Therefore, \( i_{\text{in}} (t_1) \) is determined by the ripple current of \( i_{L1} \) and \( i_{L2} \), as shown in Fig. 4.

The waveforms for the drain-to-source voltage of \( S_1 (V_{d1}) \), gate-to-source voltage of \( S_1 (V_{g1}) \), gate-to-source voltage of \( S_2 (V_{g2}) \), and leakage inductor current (\( i_{\text{L1}} \)) are shown in Fig. 10 for the ACFC with CDR. \( V_{d1} \) is zero before \( S_1 \) is turned on, which confirms the ZVS of \( S_1 \) with low electromagnetic interference (EMI) despite a small leakage inductance under all load conditions. The primary conduction loss is greater than that of conventional ACFC because of the increased \( i_{\text{L1}} (t_1) \). Nevertheless, a decrease in the primary-switching loss compensates for the increased primary conduction loss, so that the efficiency of the ACFC with CDR is higher than that of the hard-switching converter at light loads.

Waveforms for the hard-switching ACFC at 10% load are shown in Fig. 11(a). As \( S_1 \) is turned on, a hard-switching operation is observed with EMI noise before \( V_{d1} \) becomes zero. This diminishes the light-load efficiency of the hard-switching ACFC, as seen in Fig. 14(a). Waveforms of the hard-switching ACFC at 50% and 100% load are shown in Fig. 11(b) and Fig. 11(c), respectively. At 100% load

![Fig. 9. Current waveforms of the ACFC with CDR at 10% load condition.](image-url)
condition, $S_1$ almost achieves ZVS due to the increased load current, but the ACFC with CDR still shows a high efficiency.

Waveforms for the $L_{\text{M}}$-ZVS ACFC at 10% load are shown in Fig. 12 (a). For its large leakage inductance, hard-switching operation is observed with less EMI noise below 50% load condition. From 50% load, $S_1$ almost achieves ZVS as seen in Fig. 12(b). However, the increased duty cycle loss is observed at heavy load condition, which deteriorates efficiency.

Waveforms for the $L_{\text{M}}$-ZVS ACFC are shown in Fig. 13. For its reduced magnetizing inductance, soft-switching
operation is observed with less EMI noise under all load conditions. However, an enlarged primary current is observed relative to the other ACFCs, which decreases efficiency at heavy-load.

In conclusion, the ACFC with CDR achieves ZVS of $S_1$ more easily than conventional ACFC, even with a small leakage inductance. Improvements in efficiency are most evident in light-load conditions, especially, when switching loss is the dominant factor in total loss. The conventional ACFC is also able to perform ZVS with an increased resonant inductance or a reduced magnetizing inductance; however, its heavy-load efficiency is worsened by the large duty cycle loss, auxiliary switch turn-off loss and primary side conduction loss. Consequently, the ACFC with CDR has a higher efficiency with low EMI noise than ACFCs for all load conditions (see Fig. 14).

VI. CONCLUSIONS

In this paper, the ZVS operation of an ACFC with a CDR is studied. Placing the CDR in the transformer secondary, the ZVS condition can be obtained with a much smaller leakage inductance compared to conventional ACFC. Detailed ZVS analysis is conducted on the basis of steady-state analysis. The design consideration for ZVS improvements is presented. Loss analysis of the converters shows that enhanced ZVS performance contributes to improved efficiency under light-load conditions. Experimental results with a 100-W (5-V/20-A) prototype verified that the ACFC with CDR can attain ZVS of the main switch more efficiently in spite of a small leakage inductance and can achieve a high efficiency compared to the ACFCs throughout the whole load.

APPENDIX

In this appendix, state-space equations of Fig. 3 are described. By solving these equations, (1)-(4) can be obtained.

As shown in Fig. 3, there are two operation modes. In each subinterval, the converter can be denoted by the following equation:

$$\dot{x} = A_i x + B_i u \quad (i = 1, 2).$$

(16)

where $x$ is the state vector of independent states:

$$x = [i_{m}, i_{L_1}, i_{L_2}, v_{c_1}, v_{c_2}]^T.$$

(17)

and $u$ is the input vector of independent sources:

$$u = [V_g, I_p]^T.$$

(18)

From Fig. 3 (a), $A_i$ and $B_i$ can be described as follow:

$$A_i = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{(R_1 + R_2)}{L_1} & 0 & 0 & -\frac{1}{L_1} \\ 0 & 0 & 0 & -\frac{1}{L_2} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_1} & \frac{1}{C_2} & 0 & 0 \end{bmatrix}, \quad B_i = \begin{bmatrix} \frac{1}{L_1} & 0 \\ \frac{1}{N L_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_2} \end{bmatrix}. $$

(19)
From Fig. 3 (b), $A_2$ and $B_2$ can be described as follow:

\[
A_2 = \begin{bmatrix}
0 & 0 & 0 & -\frac{1}{L_w} & 0 \\
0 & \frac{R_{L1}}{L_1} & 0 & 0 & -\frac{1}{L_1} \\
0 & 0 & \frac{(R_{L2} + R)}{L_2} & 0 & -\frac{1}{NL_2} \\
0 & 0 & 0 & \frac{1}{C_r} & 0 \\
0 & 0 & \frac{1}{N C_r} & 0 & 0
\end{bmatrix}
\]

\[
B_2 = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & -\frac{1}{C_r}
\end{bmatrix}
\]

(20)

For duty cycle of main switch, $S_1$, and auxiliary switch, $S_2$, are already assumed as $D$ and $(1-D)$, respectively, the state-space averaged model which is indicated by single equivalent set is

\[
\dot{x} = Ax + Bu \ (i = 1, 2).
\]

(21)

where the equivalent matrices are defined as

\[
A = DA_1 + (1-D)A_2
\]

\[
B = DB_1 + (1-D)B_2
\]

(22)

The steady-state solution which describes the converter in equilibrium can be obtained as (21) equals to 0. Therefore, DC values indicated by capital letters can be obtained by solving the following:

\[
X = -A^{-1}BU.
\]

(23)

Unless we consider $R_{L1}$, $R_{L2}$, and $R$ on (19) and (20), $A$ becomes singular matrix. Then (23) does not provide unique solution of DC values. Consequently, $R_{L1}$, $R_{L2}$, and $R$ should be considered in case of the ACFC with CDR unlike the conventional ACFC.

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