Cross Regulation in Multi Output Converters with Renewable Energy Source

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Abstract: The multi-output DC-DC converters have been used in many applications, especially in portable and handheld consumer utilities. Single inductor multi output converters are potentially good replacement to multiple parallel converters. They can be used to produce various output voltage levels compatible with different loads, by regulating the low and variable output voltage of solar cells thus improving their reliability. The outputs of these converters being coupled, cross regulation among the output plays a major role in deciding the performance of the system. A control scheme that ensures good load and line regulation and stable system dynamics is to be implemented. The converter and controller are to be modeled and simulated, with the aim of improving the efficiency of the converter along with minimizing the cross regulation effects.

Keywords: Cross regulation, SIMO converters, renewable energy source

I. INTRODUCTION

Due to the ever increasing demand for energy, newer and better technologies are being invented and implemented worldwide. The usage of renewable energy is particularly promoted. Photovoltaic cells have a potential to meet the need of the world’s poorest with affordable clean energy, if properly utilized. AC is by far the most common way of supplying electrical energy. AC is a practical standard since both electricity generating turbines and electric motors operate with alternating currents. But, in the case of a modern household, with an independent source of energy, the situation is different. Many modern household appliances work internally on DC. For example, an induction stove or a microwave oven need to supply a magnetron with current at Giga hertz range to produce microwaves, this is commonly achieved by first transforming the 50Hz current to a normal DC current inside the machine. Another example is all household electronics such as solar panels produce electricity directly in DC, and often at low power, energy can be saved if all transformations can be done by a very efficient DC-DC converter.

II. SINGLE INDUCTOR MULTI-OUTPUT (SIMO) CONVERTERS

DC-DC converters are widely used in low- and high-power applications. Multi-output DC-DC converters have been employed with multiple inductors, in which, for M output voltage, M inductors are required. As the number of output voltages increases, the number of required inductors will also be increased which leads to an increase in the cost and size of the system.

In recent years, the multi-output DC-DC converters have been used in many portable and handheld consumer applications, such as MP3 players and digital cameras for the requirement of small-size and lightweight [1]. Conventionally, the transformer-based multi-output DC-DC converters are widely employed to provide multiple output voltages. However, the drawbacks of these transformer-type converters include the amount and cost of electronic components and circuit volume.

The single-inductor multi-output DC-DC converters were developed to effectively reduce the amount of electronic components for providing multiple output voltages. Therefore, the single-inductor multi-output three-terminal configuration is developed in order to reduce the component count and cost for multi-output DC-DC converters, including the boost, buck, buck-boost, and flyback DC-DC converters[2]. This approach reduces the number of external bulky components such as inductors and power switches, leading to decreased cost and losses in the system.

III. CROSS REGULATION

In a power supply, line and load variations are common. Line variations means that the input ripple should affect the output load variation always means a sudden change of output current. In a single inductor single output converter, output current is equal to the average current of the inductor. Suppose that the load suddenly varies[3]. Then the original balance is broken. Inductor current must be increased to get new balance. However, inductor current cannot change in a step manner. According to the volt-second law, the increment of...
inductor current during on-time must be bigger than the decrement during off-time. In other words, the duty cycle should be increased.

Load regulation in SIDO converter is more complicated. Suppose that the load of converter 1 suddenly increases, the balance of filter capacitor current whose average value is zero in steady state is broken, and then the output voltage drops. As the load regulation in a SISO converter, feedback controller adjusts duty cycle based on the amplified error, and we get a new balance [4]. However, the other converter is impacted during adjusting period. For example, the period which should serve converter 2 is used to serve converter 1, therefore a voltage drop occur at output 2. Converter 2 is not served until the error of converter 1 is reduced smaller than it. Sub-converters are alternately and interactively adjusted to reach a new steady state. This phenomenon is well known as the cross regulation.

Figure 2: Self-regulation and Cross-regulation

In time multiplexed switching scheme one switching cycle is divided into n slots with each one dedicated to drive one output. The slots are by an inductor current freewheel [5]. The operation is then transformed into a multiplexed single inductor single output operation in discontinuous conduction mode. In current shared switching, inductor current is charged and discharged to the different outputs in the subsequent slots of the switching cycle. The time multiplexing switching scheme for inductor current can be used to decouple the outputs. However, this scheme is good in DCM and not at heavy loads, as the increase in inductor peak current causes a large output voltage ripple.

Pseudocontinuous conduction mode (PCM) combines the advantages of continuous conduction mode and DCM but results in large power loss due to high inductor current level[5]. In addition, to improve efficiency, the energy delivery paths must be well arranged. In current shared switching, since the outputs are coupled, therefore, the cross regulation factor comes in, but the system can be operated in CCM and the control loops would be faster with reduced ripple at the output voltage.

IV. STATE SPACE AVERAGING

State space averaging is an approximation technique that approximates the switching converter as a continuous linear system. Final results of the state space averaging can be either a mathematical or equivalent circuit model. The mathematical model permits the designer to determine voltages, currents and small signal transfer functions of the switching converter. There are two drawbacks for the state space averaging technique. The major one is that it does not result in a general linearized model of a switching converter. The other drawback is that it requires extensions and modifications if the controlled variable is other than the duty cycle. The major advantages of this method are the establishment of a complete converter model with both steady state and dynamic quantities.

A. State space averaging of buck converter:

$$u_1 = L \frac{dx_1}{dt} + x_2$$

for $dT$ interval

$$x_1 = C \frac{dx_2}{dt} \frac{x_2}{R}$$

for $(1-d)T$ interval

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} u_1$$

(1)

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u_1$$

(2)

State space averaged state matrix state co-efficient matrix $A$ is

$$\bar{A} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} (1-d)$$

(3)

State space averaged source co-efficient matrix

$$\bar{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} d + \begin{bmatrix} 0 \\ 0 \end{bmatrix} (1-d) = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix}$$

(4)

State space averaged equations for the buck converter in matrix form are

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} u_1$$

(5)
These equations are non linear because the duty cycle \( d \) is a function of \( u_{1} \). The next step is to linearize the state space averaged equation. Any nonlinear continuous system can be approximated as a linear system within a small neighbourhood about its DC operating point. Each of the state and source variables is assumed to comprise of a steady state and dynamic term as shown below.

\[
\begin{align*}
\dot{x}_1 &= x_{10} + \dot{x}_{1} \\
\dot{x}_2 &= x_{20} + \dot{x}_{2} \\
u_{1} &= u_{10} + \dot{u}_{1} \\
d &= D + \dot{d}
\end{align*}
\]

The output voltage modulation is due primarily to changes in the input voltage, modulation in duty cycle and modulation in inductor current. Current modulation in inductor current is the sum of current modulation due to charging or discharging of the capacitor and the output current modulation due to modulation in the output voltage across the load.

\[
\begin{align*}
\dot{x}_1 &= \frac{1}{L}(x_{20} - Du_{10}) + \frac{1}{L}(D\dot{u}_{1} + d\dot{u}_{10}) \\
\dot{x}_2 &= \frac{1}{C}(x_{10} - \dot{x}_{1}) + \frac{1}{C}(\dot{x}_{1} - \frac{\dot{x}_{2}}{R})
\end{align*}
\]

The conventional averaging method does not suit well for SIMO converters since they average the inductor current over the entire cycle, which, in the process, ignores the ripple information. Thus, a mode-by-mode averaging of the inductor current has been done to model the converter.

The average inductor current \( (i_L) \) and output capacitor voltages \( (v_1 \) and \( v_2) \) are considered to be the state variables to the system. The duty cycles \( (d_1) \) and \( d_2 \) are the control variables, and disturbances are observed at the input voltage \( (v_{in}) \) and the output loads \( (i_1 \) and \( i_2) \). Thus, the matrix representation of the state variable and input variable is \( x = [i_L, v_1, v_2]T \), \( u = [v_{in}, i_1, i_2]T \).

**V. SIMULATION RESULTS**

**A. Simulation diagram:**

The simulation is done for a single inductor dual output buck converter. Buck converter was chosen because the behavior is rather more linear. The input voltage was varied and the corresponding output voltages were observed. Also, the inductor current was measured.

![Simulation diagram of SIDO buck converter](image)

![Output voltages](image)

![Inductor current](image)

**VI. CROSS COUPLING TRANSFER FUNCTIONS**

The inductor current ripple-based modeling technique analyzes the steady state and the dynamic behavior of the system. In the SIMO example presented, the system has been represented with three state variables \( (i_L, v_1, \) and \( v_2) \) and two independent control variables \( (d_0 \) and \( d_1) \). The system can be controlled efficiently by proper management of the state feedbacks from the self-output and cross-output to aptly control the control and cross-coupled transfer functions. Realizing physically, for
example, for a two output SIMO converter, whenever there is a load step in one output (viz \( V_1 \)), the corresponding output capacitor tends to drive the output to maintain the output level, which leads to an increase in the duty cycle of the corresponding output switch. Since the sum of all the duty cycles is one, the increase in the duty cycle of the output channel of \( V_1 \) signifies a decrease in the duty cycle of the output switch of the other channel (for \( V_2 \)). As the duty cycle for \( V_1 \) decreases, the output capacitor in channel two has to be driven to regulate \( V_2 \), which leads to an increase in the output voltage. Thus, if the capacitor current information from the self-loop output (\( V_1 \)) is fed to the cross-loop output (\( V_2 \)), the cross-regulation effect should get reduced. Based on this concept, a generalized state feedback method that would enable us to obtain the coefficients for the self-loop and cross loop compensators is the most viable.

The open-loop control and cross-coupling transfer functions for the converter with the given set of specifications were obtained. The Bode plots, obtained from the Matlab for the transfer functions calculated and given here, for the control and cross-coupling transfer functions for \( V_1 \) and \( V_2 \) are shown in figures 6 and 7, respectively. The blue plot in Figure 6 shows the control transfer function \( \hat{V}_1(s)/\hat{D}_1(s) \) and indicates the existence of a right-half plane (RHP) zero at 105 Hz, while the red plot gives the cross-coupling transfer function \( \hat{V}_1(s)/\hat{D}_0(s) \). The green plot shows the cross-coupling plot in Figure 7, while the blue indicates the control transfer function for \( V_2 \). Validation of open-loop steady-state performance in simulation with the equivalent calculations is shown in Fig. 5. With a wide variation in duty cycles, the ideal level simulation matches well with the calculated values. The deviation in ideal simulation from the calculated values is less than 0.05%. It needs to be noted that calculation using the conventional small signal modeling does not match with the simulations and varies widely. The proposed ripple-space modeling shows that the topology can also achieve negative output voltages, but the conventional state space does not show that.

**VII. CONCLUSION**

Several voltage and current control techniques have been applied for SIMO converters to improve the dynamic performance in continuous conduction mode (CCM) or discontinuous conduction mode (DCM) operation. SIMO converters can be used to the best of their potentialities if cross regulation effects are avoided. Suitable control strategies have to be adopted to achieve this. Among the various control methods a state feedback control method preceded by a ripple based modeling is the most effective.

The applications of SIMO converters can be best utilized with the help of MOB (Multi output Boost) converters. Series regulated DC voltages may be required in different low- and high-power applications. One of the most interesting applications of this new family of DC-DC converters is the boosting and regulating the low and variable output voltage of renewable energy for the DC link of grid connected systems, based on multilevel inverters.

**VIII. REFERENCES**


