Small Signal Analysis for LLC Resonant Converter

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Abstract—In this paper, small signal characteristic of a LLC resonant converter is analyzed. LLC resonant converter was been reported in many papers recently because of its simple structure, high efficiency and high switching frequency capability. In order to make practical use of this topology, understanding its small signal characteristic is essential to design the control loop. For PWM converter, state space average method is well established and verified. For resonant converter, because of the different ways of operation, state space average model cannot give satisfactory result. In this paper, simulation method is used to derive the small signal model of resonant converter. With this method, Series Resonant Converter and LLC resonant converter were been analyzed. Finally, a prototype of LLC resonant converter was built and tested to verify the results get from previous analysis.

I. Introduction

High power density and low profile are two trends for today’s power supply market. To meet these trends, topologies can provide high efficiency and high switching frequency capability will be the winner. For PWM topologies like phase shift full bridge and half bridge converters, switching loss will prevent high switching frequency operation. LLC resonant converter, which is shown in Fig.1, has been discussed in many papers recently for its high efficiency, low switching loss and low stress on components [1]. It also provides a unique characteristic, which is very important for front-end converter. For LLC resonant converter, it can be optimized with high input voltage while still capable of cover wide input range. For front end DC/DC converter, LLC resonant converter can provide more than 3% efficiency improvement over PWM converter.

Steady state operation and characteristic of LLC resonant converter have been discussed in detail in previous papers. However, those analyses were not enough for the design of LLC resonant converter. To design the converter, a feedback control must be designed to provide a stable and fast system. To design the control loop, small signal characteristic of LLC resonant converter need to be revealed.

For PWM converter, state space average method has been widely used. State space average method provides simple and accurate solution for up to half switching frequency. It has been verified and a theoretical system been established. With the small signal model derived from state space average method, small signal characteristic of PWM converter can be studied and control circuit can be designed accordingly.

Unfortunately, state space averaging method cannot be applied for frequency controlled resonant converter. This is because of the totally different ways of energy processing methods for these two kinds of power converter. For PWM converter, the natural frequency of the linear network (output filter) is much lower than the switching frequency. The modulation of the converter is achieved through the low frequency content in the control signal. With this character, the average method can provide approximate linear solution of the nonlinear state equations. The derived model has a continuous form and is accurate up to half of switching frequency. However, for resonant converter, the switching frequency is close to the natural frequency of the linear network (resonant tank). The states contain mainly switching frequency harmonics instead of low frequency content in PWM converter. The modulation of the resonant converter is achieved by the interaction between switching frequency and resonant frequency. Since average method will eliminate the information of switching frequency, it cannot predict the dynamic performance of resonant converter [2] [3] [4].

In the past, several methods were tried to solve this problem. Some of them are very complex and difficult to use. In this paper, a simulation-based method is used to derive the small signal characteristic of frequency controlled resonant converter. This method uses simulation tools to emulate the function of impedance analyzer to get the small signal response of the converter. It needs a time domain simulation model of the converter, which is easy and necessary for every design. It is a very effective method to deal with complex topology, which is difficult to deal with conventional method.

This paper is organized in following way. The description of the method was given in Section II. Then with
this method, a Series Resonant Converter is analyzed and the results were shown in Section III. In section IV, the small signal characteristic of LLC resonant converter is analyzed. Also, in this section, test result is showed to verify the analysis result. Finally, some discussion and directions for future work is presented in section V.

II. Switching Model Based Small Signal Analysis

In this part, the method used in this paper to derive the small signal characteristic of a switch mode power supply will be discussed. This method is based on switching model of the converter under investigation. For every converter, switching model is a necessary to understand and design the converter. So, there is no extra modeling effort needed for this method. The method is tried to emulate the function of a network analyzer. It can be described in following steps.

Step 1: Simulate the switching model of the converter without perturbation to steady state and record the information of the variables of interest. For example, if the control to output characteristic is going to be analyzed, the steady state information of output voltage and control voltage should be recorded.

Step 2: Inject a small perturbation with given frequency into the converter. Then simulate the converter with perturbation to new steady state and record the information of interested variable.

Step 3: Compare the information got from step 1 and 2, the divide the difference of these two simulation steps, a small signal characteristic of the converter at given operation condition and perturbation frequency is got, which is a point on the bode-plot.

With above simulations, we got the small signal characteristic of the converter at given operating condition and given perturbation frequency. By sweeping the perturbation frequency, the bode-plot of the system small signal characteristic at a given condition can be derived.

Since this method is based on switching model of the converter, it is easy to use. The drawback of this method is that to get the whole picture, large quantities of simulations need to be performed, which is time consuming. Also, another drawback for this method is that it is difficult to extract the small signal model of the system when the system is complex.

III. Small Signal Analysis for Series Resonant Converter

Base on the method described in previous part, small signal analysis of series resonant converter as shown in Fig. 3 is analyzed in this part. The purposes of this analysis have two fold:

First, this analysis will verify the method. Because for series resonant converter, its small signal characteristic has been investigated by many people. In [6], with describing function method, the small signal model of series resonant converter is showed in detail. It can be used to verify the results get from this simulation.

Second, this analysis will provide baseline to compare with for LLC resonant converter. The operation of LLC resonant converter has some similarity with series resonant converter. When it is working with switching frequency higher than resonant frequency, it is a series resonant converter. Compare the small signal characteristic of LLC resonant converter with Series resonant converter can provide better understanding of the new characteristic of LLC resonant converter.
Fig. 4 and Fig. 5 show the control to output small signal characteristic of series resonant converter. For the simulation circuit, following parameters were used: \( L_r = 28 \mu H, C_r = 22 \text{nF}, C_o = 220 \mu F, \) turns ratio 4:1, and \( Q_s = 4.5. \) With those parameters, the resonant frequency of the SRC is 200 kHz.

In the graph, the x-axis is the frequency for bode plot; y-axis is the magnitude in DB or phase in degree, and z-axis is the running parameter, which is the switching frequency. This is because for resonant converter, to regulate the output voltage, the switching frequency will be varied. For different switching frequency, the small signal model will be different. From these results, following things can be clearly identified:

1. Beat frequency double pole. This is a special characteristic for resonant converter \([5][6]\). As switching frequency changes, a double pole with frequency at the difference of switching frequency and resonant frequency will move accordingly too. Finally, when switching frequency is close enough to resonant converter, this double pole will split, one merge with low frequency pole formed by output cap and load, one move to higher frequency.

2. Beat frequency dynamic. Since the low frequency gain is proportional to the slope of DC characteristic of series resonant converter. When the operation frequency moves close to the resonant frequency, the slope gets flat and low frequency gain drops. When switching frequency equals to resonant frequency, the gain will be zero. As can be clearly seen on the graph, when switching frequency is close to resonant frequency, the control to output gain will be very low. A gap can be observed on the graph.

3. The phase has a 180-degree jump around resonant frequency. This is because of the change of the DC characteristic slope. Switching frequency lower than resonant frequency, with increasing switching frequency, gain will increase, so the phase delay at DC will be zero. When the switching frequency is higher than resonant frequency, as switching frequency increases, gain will decrease, which will give 180 degree at DC.

4. Low frequency pole. This pole is caused by the output capacitor and load. With lighter load, this pole will move to lower frequency.

From above simulation results, the small signal characteristic of a series resonant converter is derived. Beat frequency double pole and beat frequency dynamic are observed. Compare with results reported in \([6]\), a very good match is achieved. From this result, we can be more confident with the method.

IV. Small Signal Analysis for LLC Resonant Converter

In this part, the small signal characteristic of LLC resonant converter will be studied. The parameters used for this study are: \( L_r = 14 \mu H, C_r = 25 \text{nF}, L_m = 60 \mu H, \) turns ratio: 4:1, load resistance is 2.5 ohm and \( C_o = 1200 \mu F. \) Before we study the small signal characteristic of LLC resonant converter, let’s have a look of the operation of LLC resonant converter first.

Fig. 5 shows the gain characteristic of LLC resonant converter. The operation regions are shown in the graph. From the graph it can be see that the gain characteristic of LLC resonant converter can be divided into three regions.

Region 1: switching frequency is higher than resonant frequency of \( L_r \) and \( C_r. \) In this region, the \( L_m \) will never participate in resonant, the converter operate very similar to series resonant converter except now \( L_m \) is also work as the load of series resonant converter.

Region 2: this region is defined by series resonant frequency and frequency at which the DC gain characteristic changes slope. For front end DC/DC application, we will design the converter operate in region 1 and 2.

Region 3: in this region, the converter work in ZCS condition. This is not a desired operation region. For completion of the work, small signal characteristic of region 3 is also studied here.

Following the steps in section II, the control to output characteristic of LLC is shown in Fig. 7 and Fig. 8.
From Fig.7 and Fig.8, it can be clearly seen that the small signal characteristic of the LLC resonant converter can also be divided into three regions too according to three region in gain characteristic. In each region, the small signal characteristic is different from other region.

From the curves we can see, the beat frequency dynamic now happens at lower resonant frequency. At the resonant frequency of \( L_r \) and \( C_r \), there is no big change of small signal characteristic for the converter.

Because our operating region is limited to region 1 and region 2, next detail information will be discussed in these two regions.

In Fig.9 and 10, the small signal characteristics of region 1 are shown. When LLC converter works in this region, it works like a series resonant converter. \( L_m \) will act as the load of the series converter. From the simulation result we can see the beat frequency double pole. For the low frequency pole caused by output filter and load, the frequency is moving because of the impact of \( L_m \). Finally, when switching frequency is very close to resonant frequency of \( L_r \) and \( C_r \), the beat frequency double pole will split, one pole merge with low frequency pole while the other one move toward higher frequency.

In Fig.11 and 12, the small signal characteristics of region 2 are shown. In this region, \( L_m \) will participate into the resonant in each switching cycle. From simulation results, the small signal characteristic of LLC resonant converter is pretty stable in this region. Two low frequency poles can be seen at frequency of output filter and load.
Another important aspect, which might affect the small signal characteristic, is load condition. As seen in PWM converter, when load becomes lighter, the converter will run into DCM, the low frequency double pole will split and separate.

From Fig.13 to Fig. 16, the small signal characteristics of LLC converter in region 1 and 2 for different load conditions are shown. From the simulation results, it is interesting to see some phenomena very similar to PWM converter.

In region 1, at heavy load, the small signal characteristic is stable in respect to load change. When load reduce to some level, the two poles will split, one pole move to lower frequency and one pole move to higher frequency. This phenomenon is very similar to the PWM converter.

In region 2, however, the situation is a little bit complex. From the simulation results we can see, as load change from heavy load to light load, the small signal characteristic changes in different fashion. First, the two low frequency poles split as load change from heavy load to light load. At some point, the two poles becomes a double pole. As we continue reduce the load, the double pole eventually split and one pole move to high frequency while the other one move to lower frequency as in region 1.

To verify the simulation results, a test circuit was built with same parameters as used in simulation. Following are the test results compare with simulation results. As we can see, the simulation-results are very closely matching the test results.
its small signal characteristic can be divided into three regions according to its DC characteristic.

When LLC converter works in switching frequency higher than resonant frequency, it is very similar to series resonant converter.

When LLC resonant converter works in switching frequency lower than resonant frequency, the small signal characteristic is pretty stable with change of switching frequency.

Also, the impact of changing load on small signal characteristic of LLC converter is been investigated.

In this paper, simulation method is used to investigate the small signal characteristic of resonant converter. This approach can give us accurate and relative quick results. The drawback is that this method gives us less insight in understanding the model of the converter. To further utilize the data generated from above analysis, system identification should be performed to extract the small signal model of the converter, which can give us a simple and more effective way in design the controller for resonant converter.

REFERENCES


