US010491123B2

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Wang et al.

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(45) **Date of Patent: Nov. 26, 2019**

(54) **MODULAR PARALLEL TECHNIQUE FOR RESONANT CONVERTER**

(71) Applicant: **Murata Manufacturing Co., Ltd.**, Nagaokakyo-shi, Kyoto-fu (JP)

(72) Inventors: **Hongliang Wang**, Markham (CA); **Yang Chen**, Markham (CA); **Yan-Fei Liu**, Markham (CA); **Jahangir Afsharian**, Markham (CA); **Zhihua Yang**, Markham (CA); **Bing Gong**, Markham (CA)

(73) Assignee: **MURATA MANUFACTURING CO., LTD.**, Kyoto (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/757,552**

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(86) PCT No.: **PCT/US2016/052293**
§ 371 (c)(1),
(2) Date: **Mar. 5, 2018**

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PCT Pub. Date: **Mar. 23, 2017**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**

H02M 3/335	(2006.01)
H02M 3/28	(2006.01)

(52) **U.S. Cl.**
CPC ***H02M 3/285*** (2013.01); ***H02M 3/33592*** (2013.01)

(58) **Field of Classification Search**
CPC H02M 3/335; H02M 3/33576; H02M 3/33592; H02M 3/3376
See application file for complete search history.

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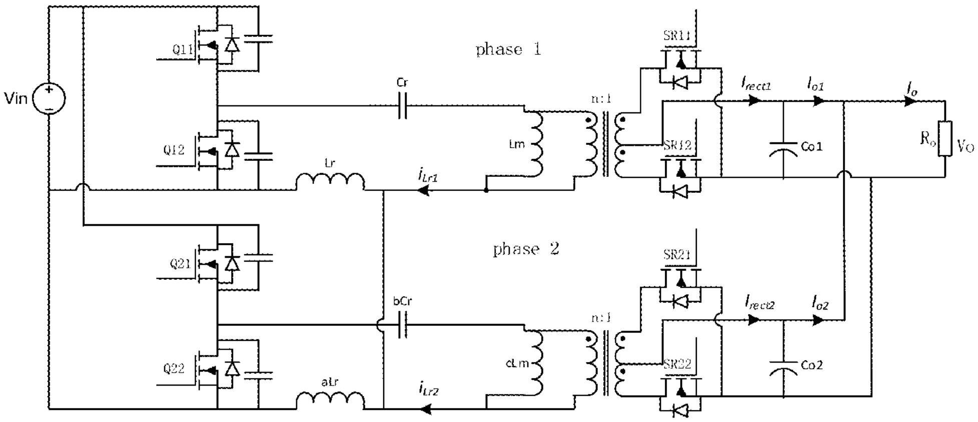
Primary Examiner — Jeffrey A Gblende
Assistant Examiner — Nusrat Quddus
(74) *Attorney, Agent, or Firm* — Keating & Bennett, LLP

(57) **ABSTRACT**

An LLC resonant converter includes a first phase with a first primary circuit and a second phase with a second primary circuit. The first primary circuit includes a first shared inductor, and the second primary circuit includes a second shared inductor. The first and second shared inductors are connected in parallel with each other. The first and second primary circuits do not include a capacitor that is connected in parallel with each other.

5 Claims, 32 Drawing Sheets



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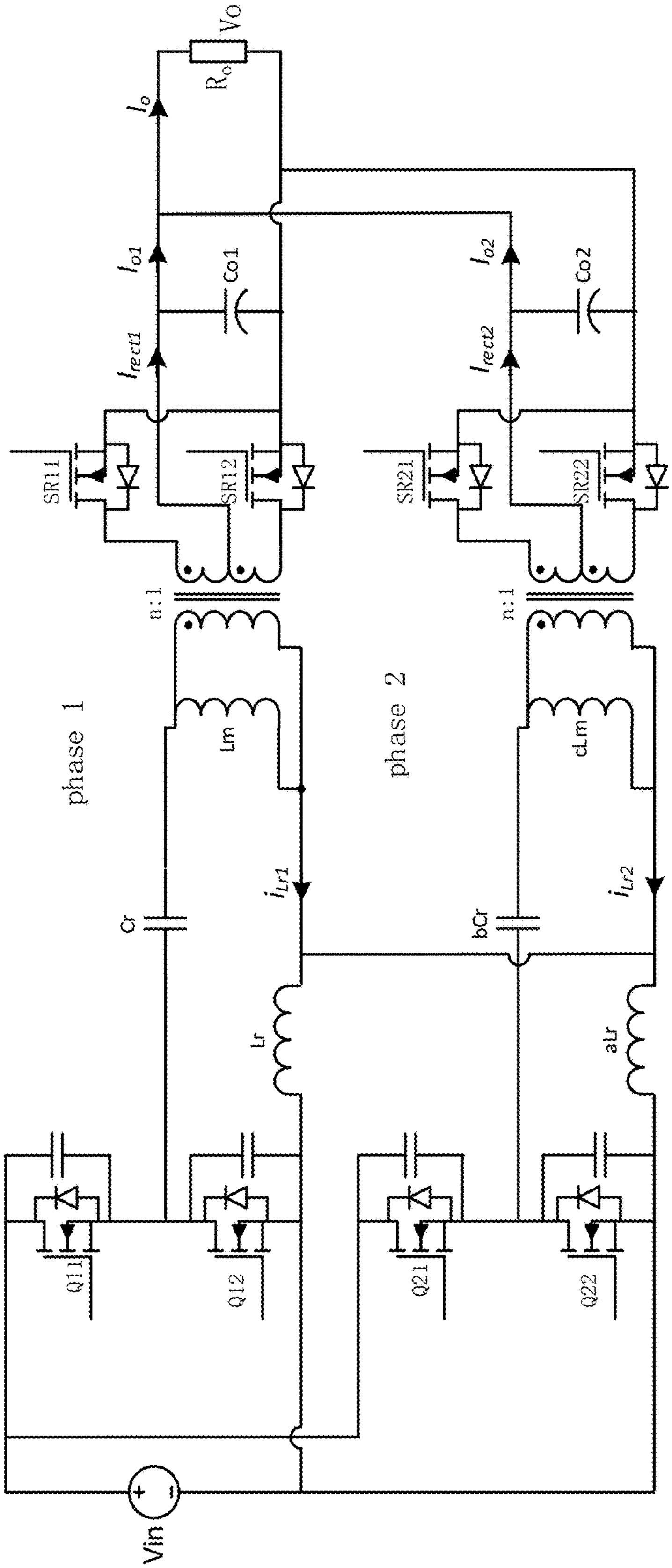
VO
Ro
Io
Io1
Co1
Irect1
Io2
Co2
Irect2
SR11
SR12
SR21
SR22
n:1
n:1
phase 1
phase 2
Lm
cLm
iLr1
iLr2
Cr
bCr
Lr
aLr
Q11
Q12
Q21
Q22
+
-
Vin

Fig. 1

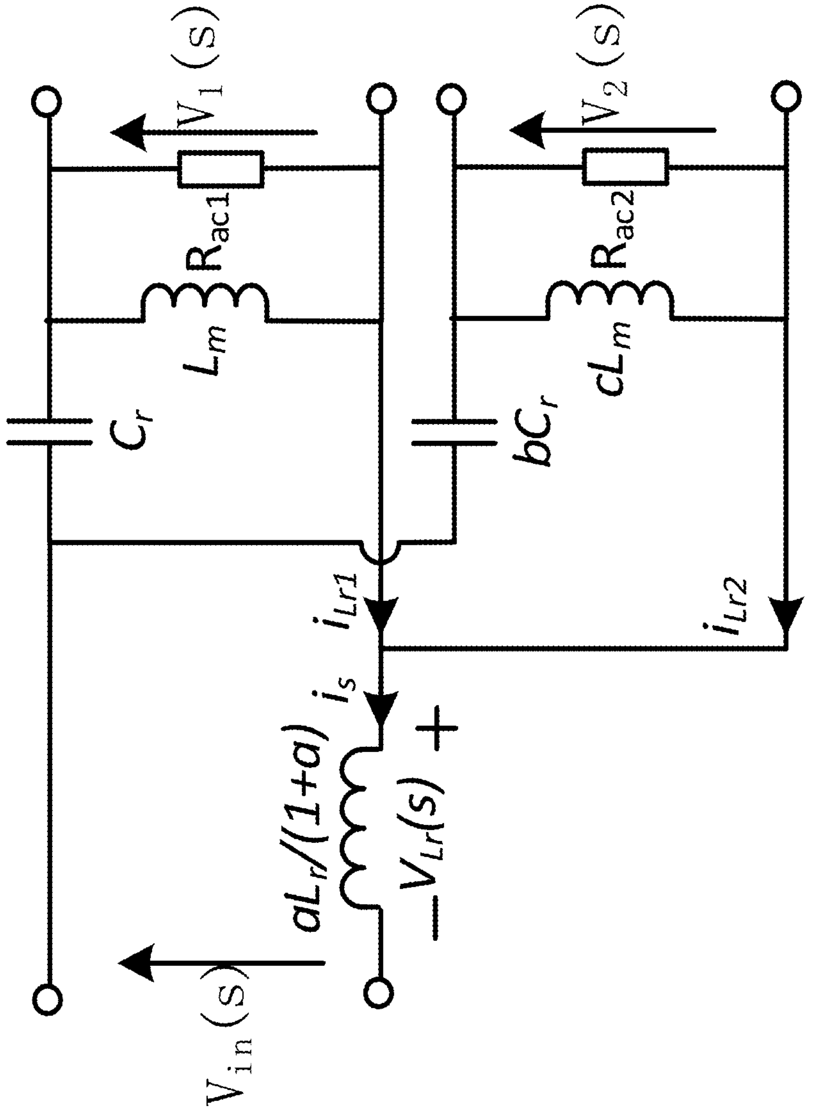

Fig. 2

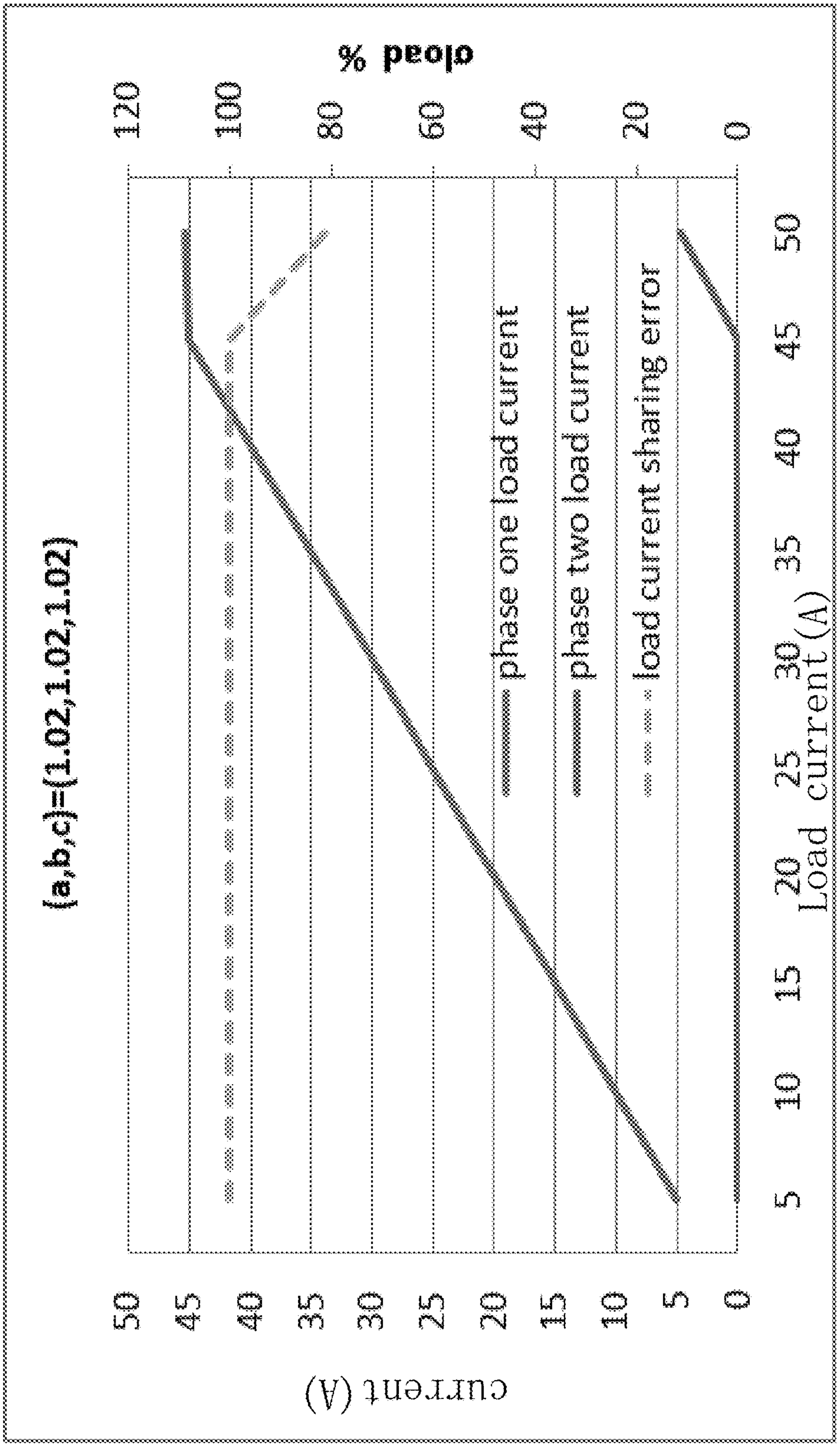

Fig. 3
PRIOR ART

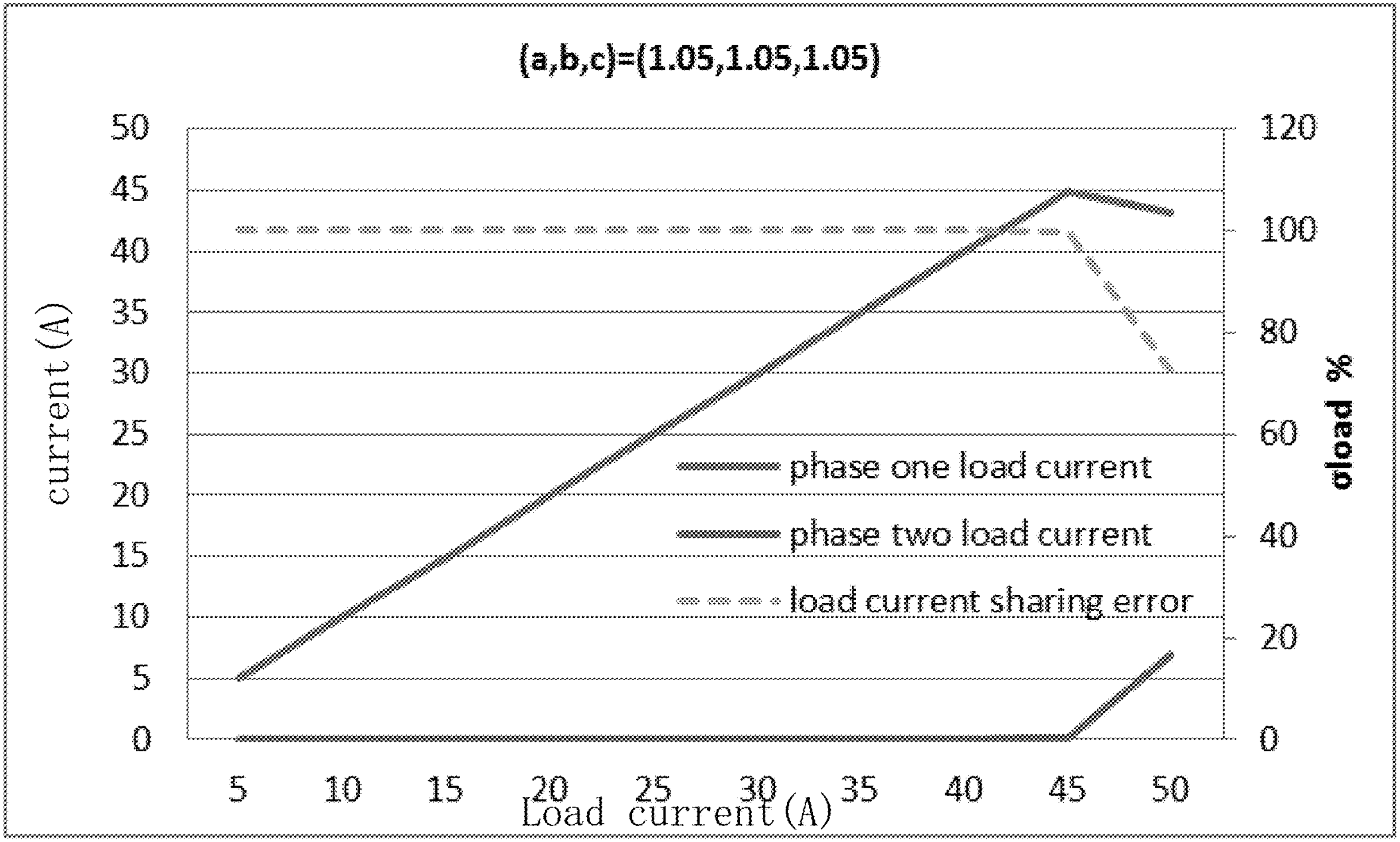

Fig. 4
PRIOR ART

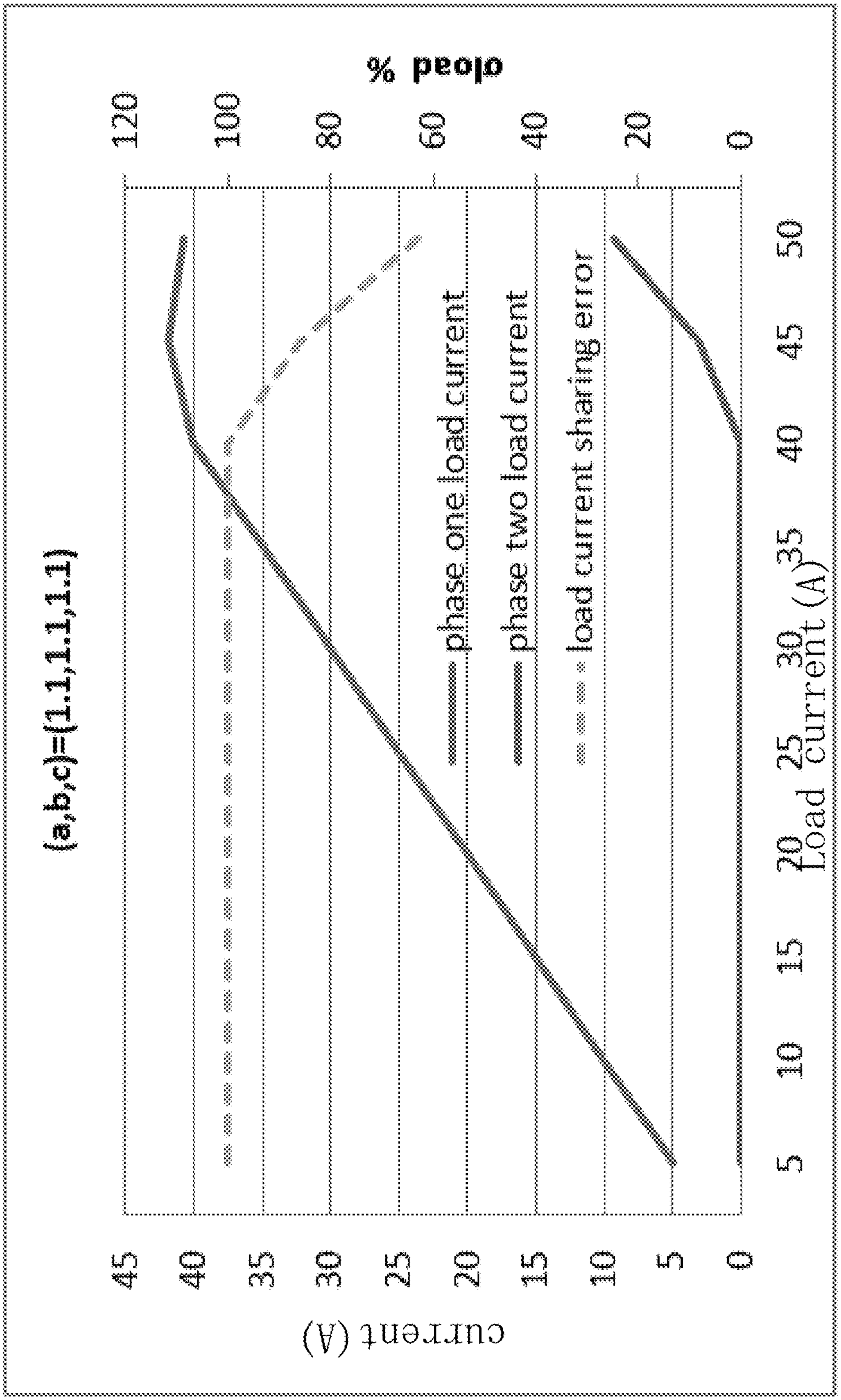

Fig. 5
PRIOR ART

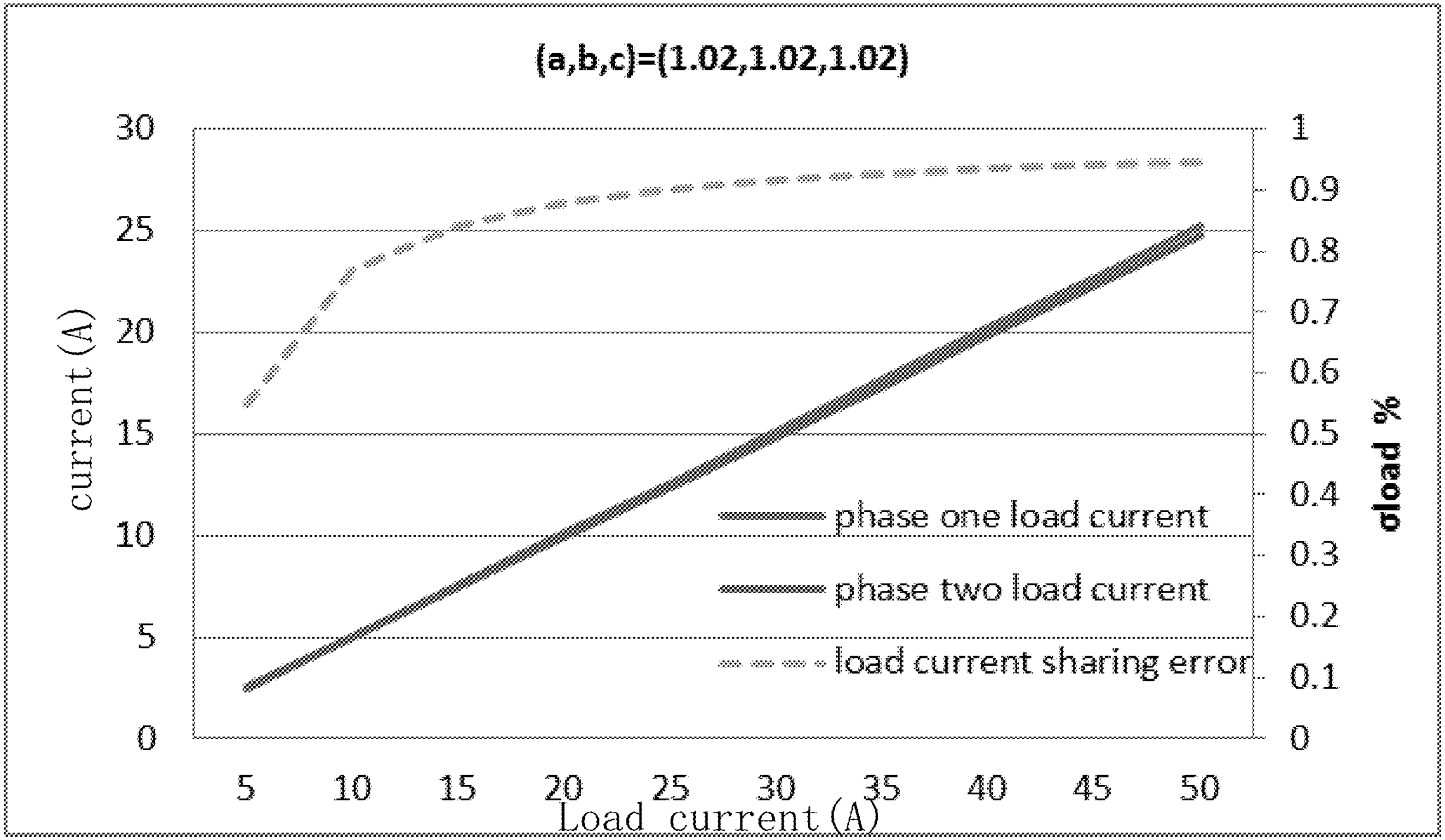
(a,b,c)=(1.02,1.02,1.02)
current (A)
30
25
20
15
10
5
0
σload %
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40
45
50
Load current (A)
phase one load current
phase two load current
load current sharing error

Fig. 6

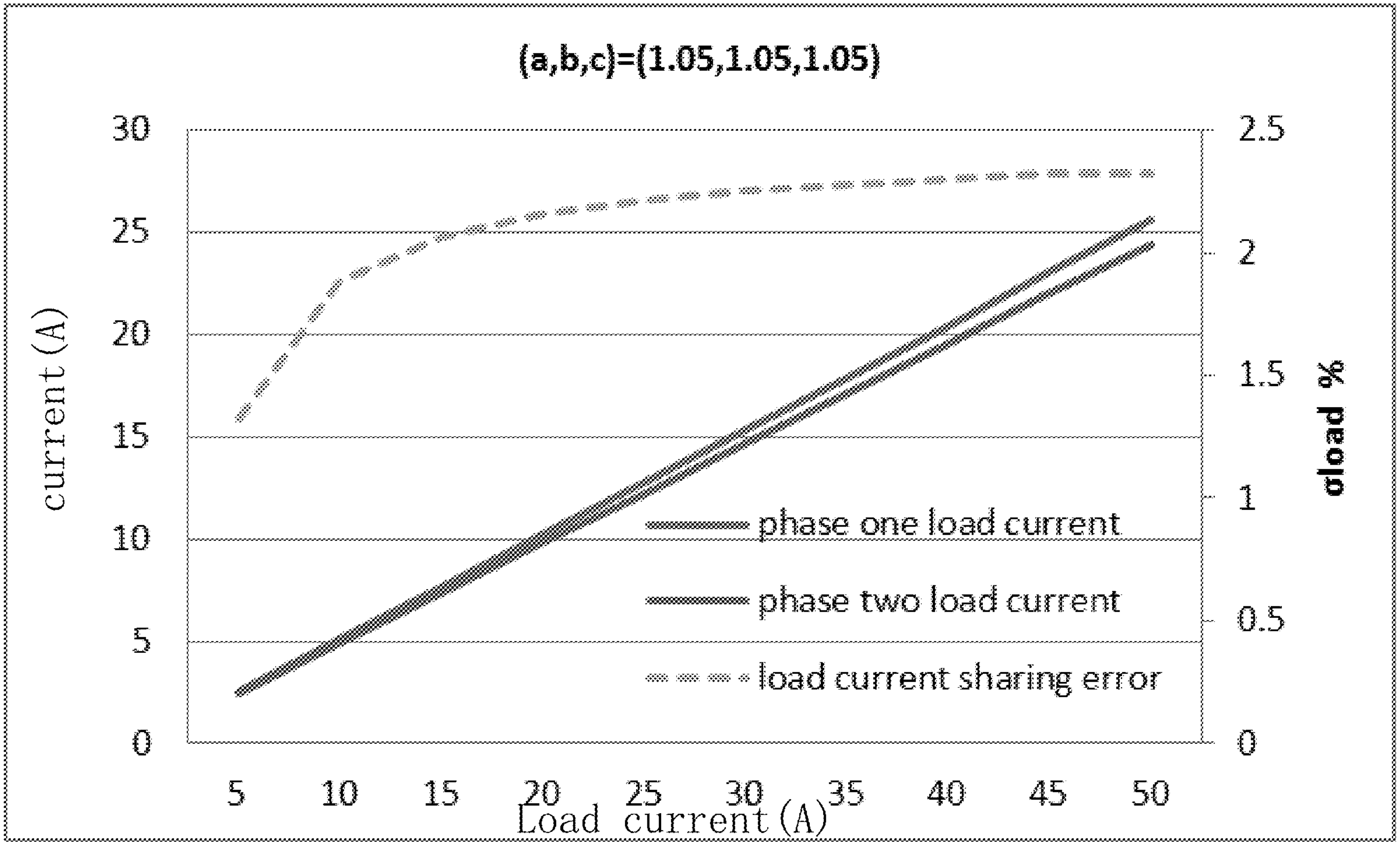
(a,b,c)=(1.05,1.05,1.05)
current (A)
30
25
20
15
10
5
0
oload %
2.5
2
1.5
1
0.5
0
phase one load current
phase two load current
load current sharing error
5
10
15
20
25
30
35
40
45
50
Load current (A)

Fig. 7

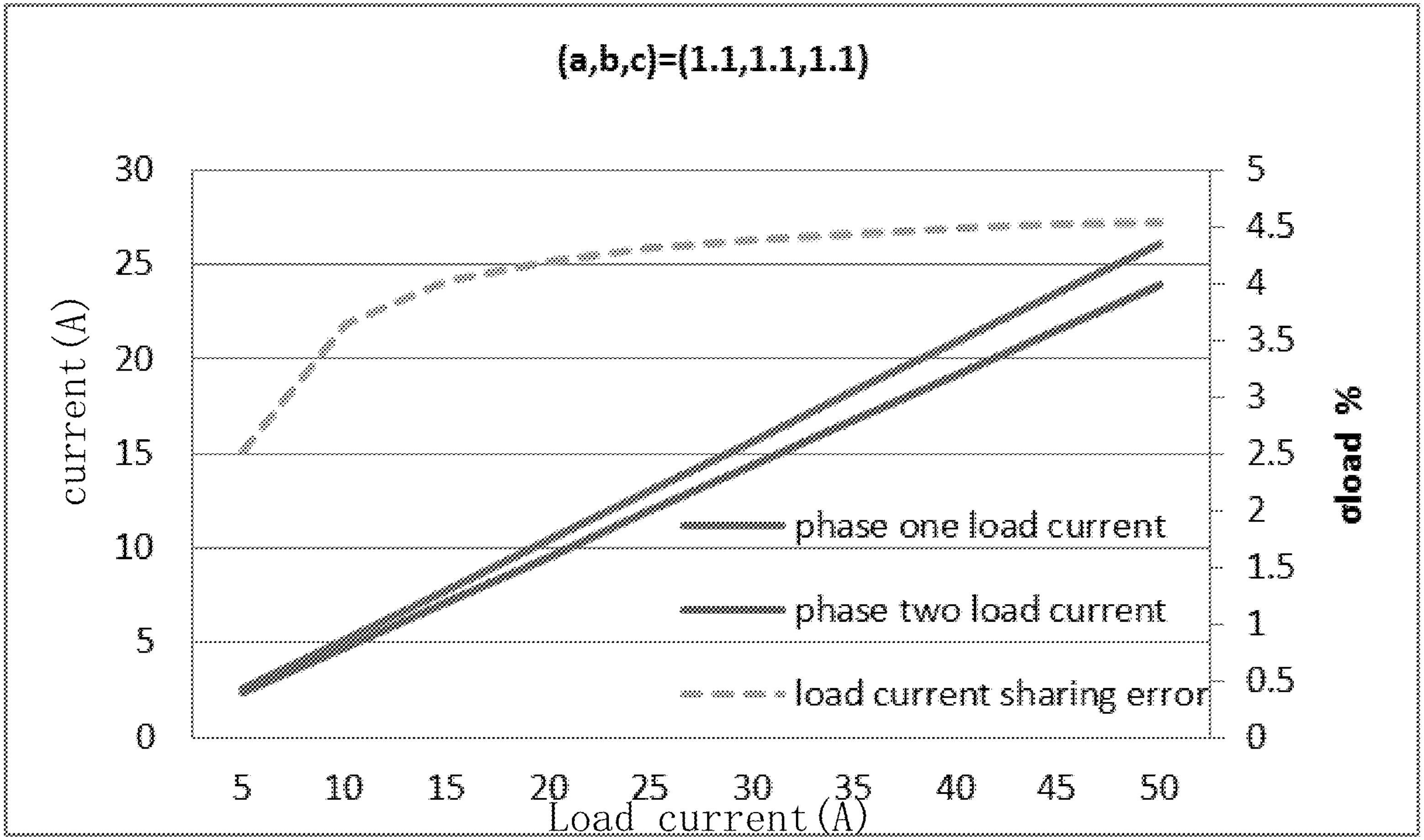
(a,b,c)=(1.1,1.1,1.1)
current (A)
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
Load current (A)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
oload %
phase one load current
phase two load current
load current sharing error

Fig. 8

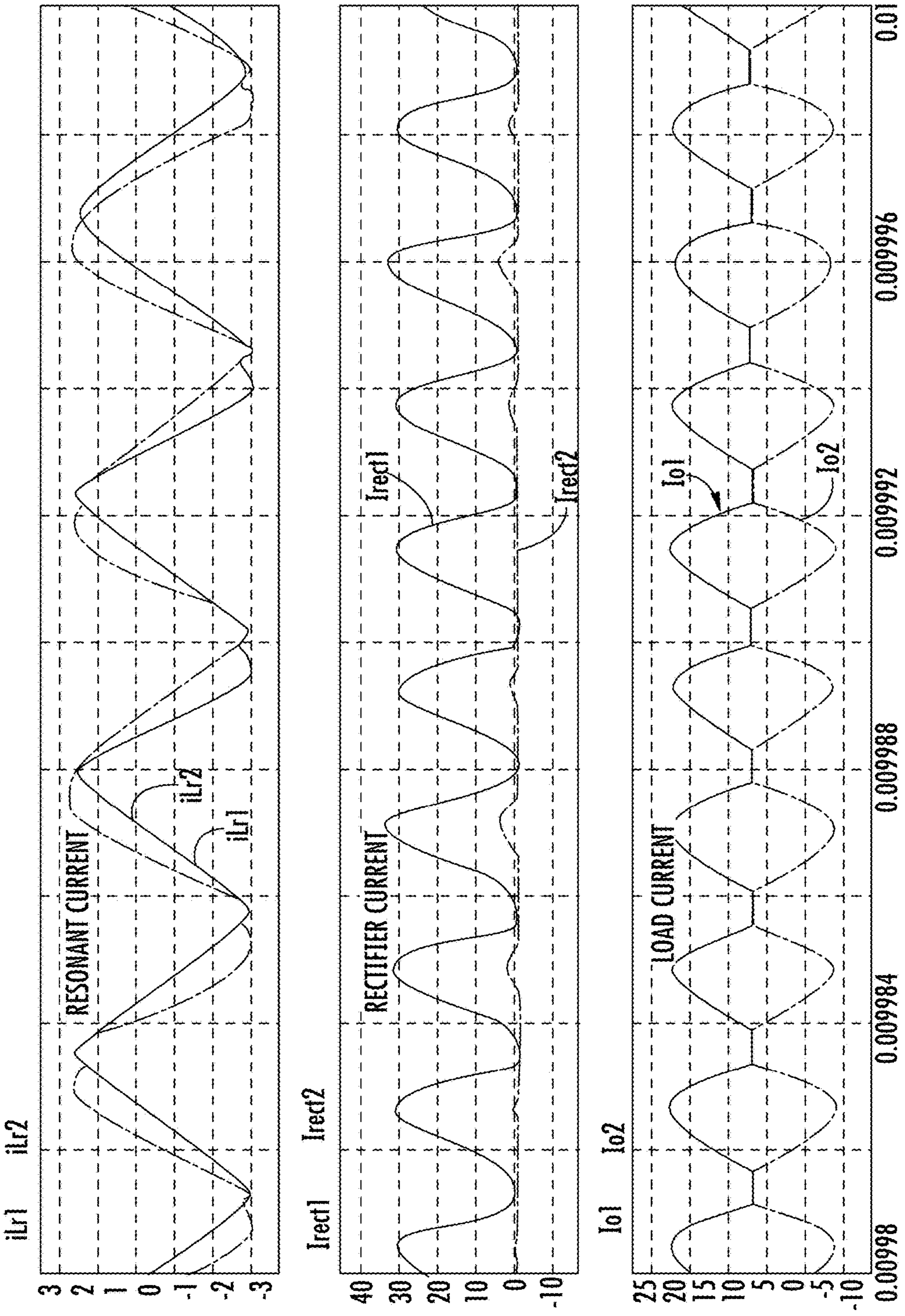
iLr1
iLr2
RESONANT CURRENT
iLr2
iLr1
3
2
1
0
-1
-2
-3
Irect1
Irect2
RECTIFIER CURRENT
Irect1
Irect2
40
30
20
10
0
-10
Io1
Io2
LOAD CURRENT
Io1
Io2
25
20
15
10
5
0
-5
-10
0.00998
0.009984
0.009988
0.009992
0.009996
0.01

FIG. 9

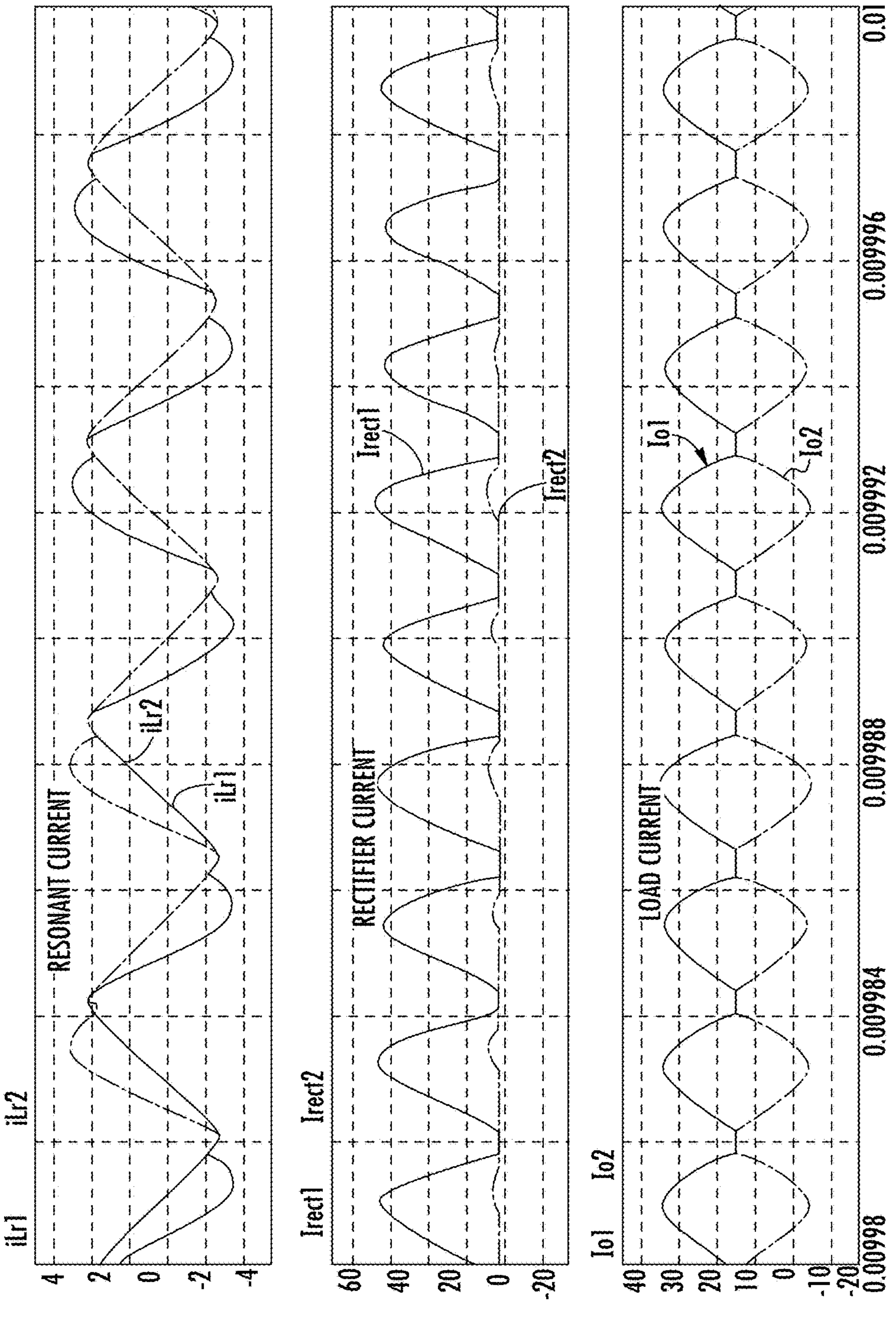

FIG. 10
PRIOR ART

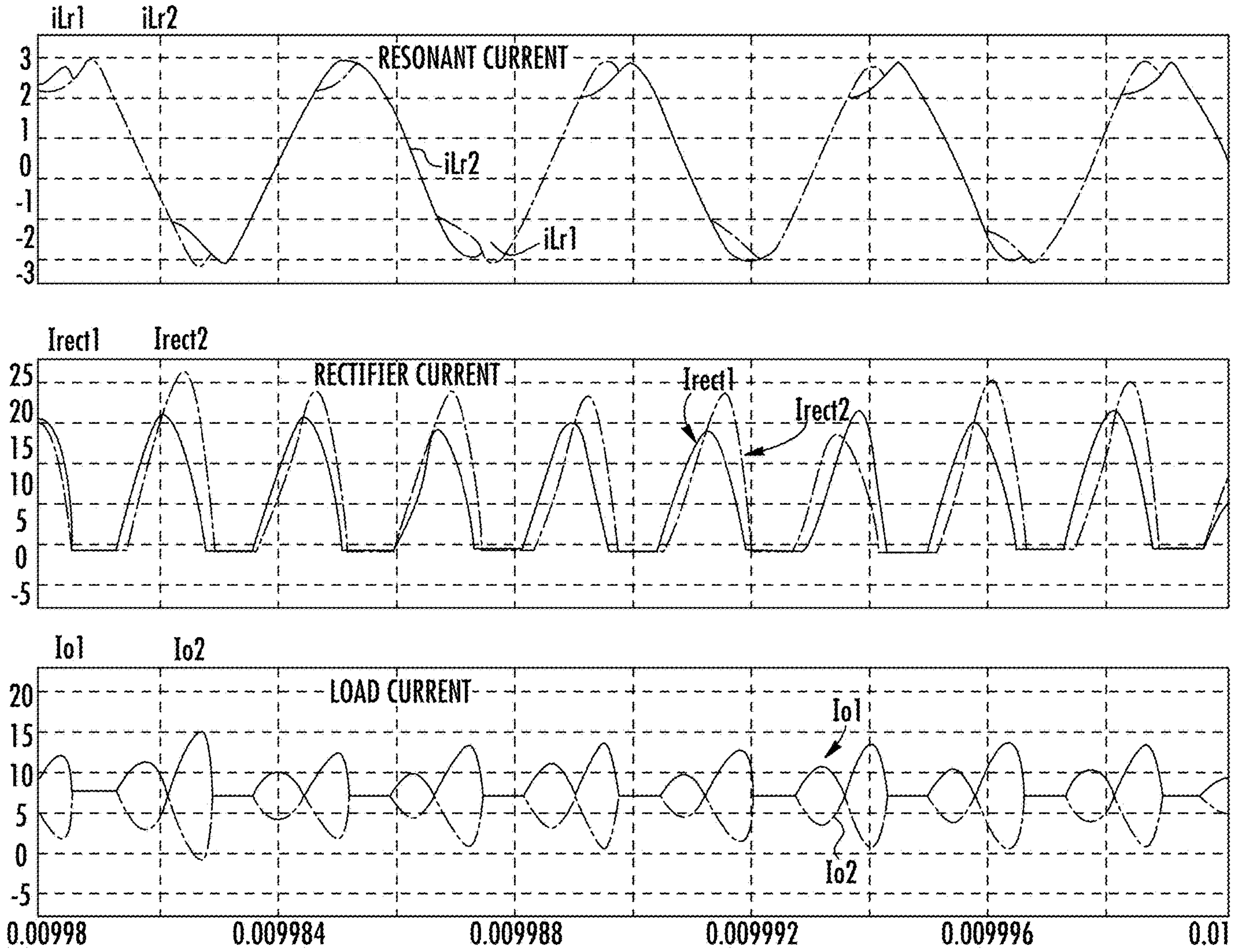
iLr1
iLr2
RESONANT CURRENT
iLr2
iLr1
3
2
1
0
-1
-2
-3
Irect1
Irect2
RECTIFIER CURRENT
Irect1
Irect2
25
20
15
10
5
0
-5
Io1
Io2
LOAD CURRENT
Io1
Io2
20
15
10
5
0
-5
0.00998
0.009984
0.009988
0.009992
0.009996
0.01

FIG. 11

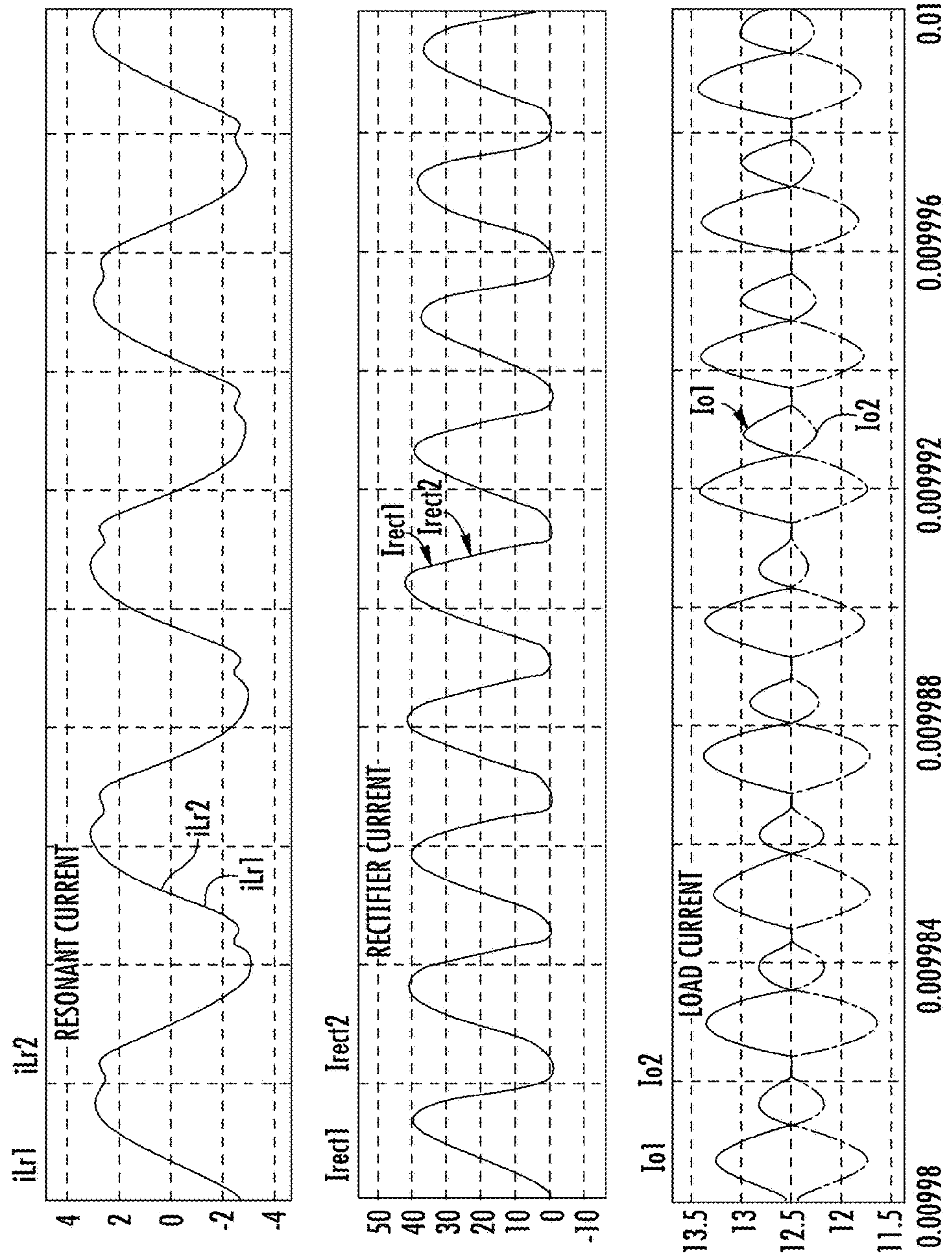
iLr1
iLr2
RESONANT CURRENT
iLr2
iLr1
4
2
0
-2
-4
Irect1
Irect2
RECTIFIER CURRENT
Irect1
Irect2
50
40
30
20
10
0
-10
Io1
Io2
LOAD CURRENT
Io1
Io2
13.5
13
12.5
12
11.5
0.00998
0.009984
0.009988
0.009992
0.009996
0.01

FIG. 12

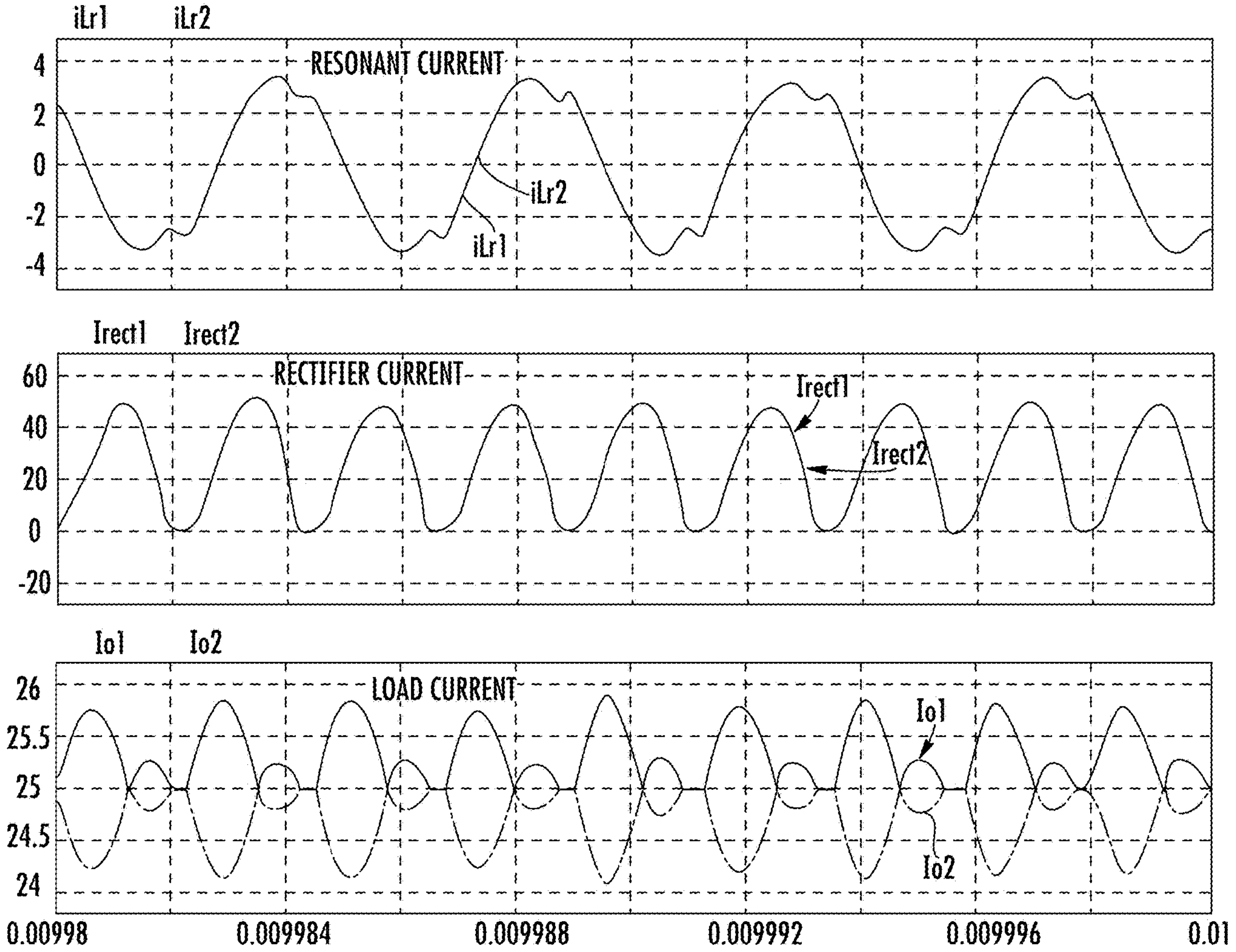
iLr1
iLr2
RESONANT CURRENT
4
2
0
-2
-4
iLr2
iLr1
Irect1
Irect2
RECTIFIER CURRENT
60
40
20
0
-20
Irect1
Irect2
Io1
Io2
LOAD CURRENT
26
25.5
25
24.5
24
Io1
Io2
0.00998
0.009984
0.009988
0.009992
0.009996
0.01

FIG. 13

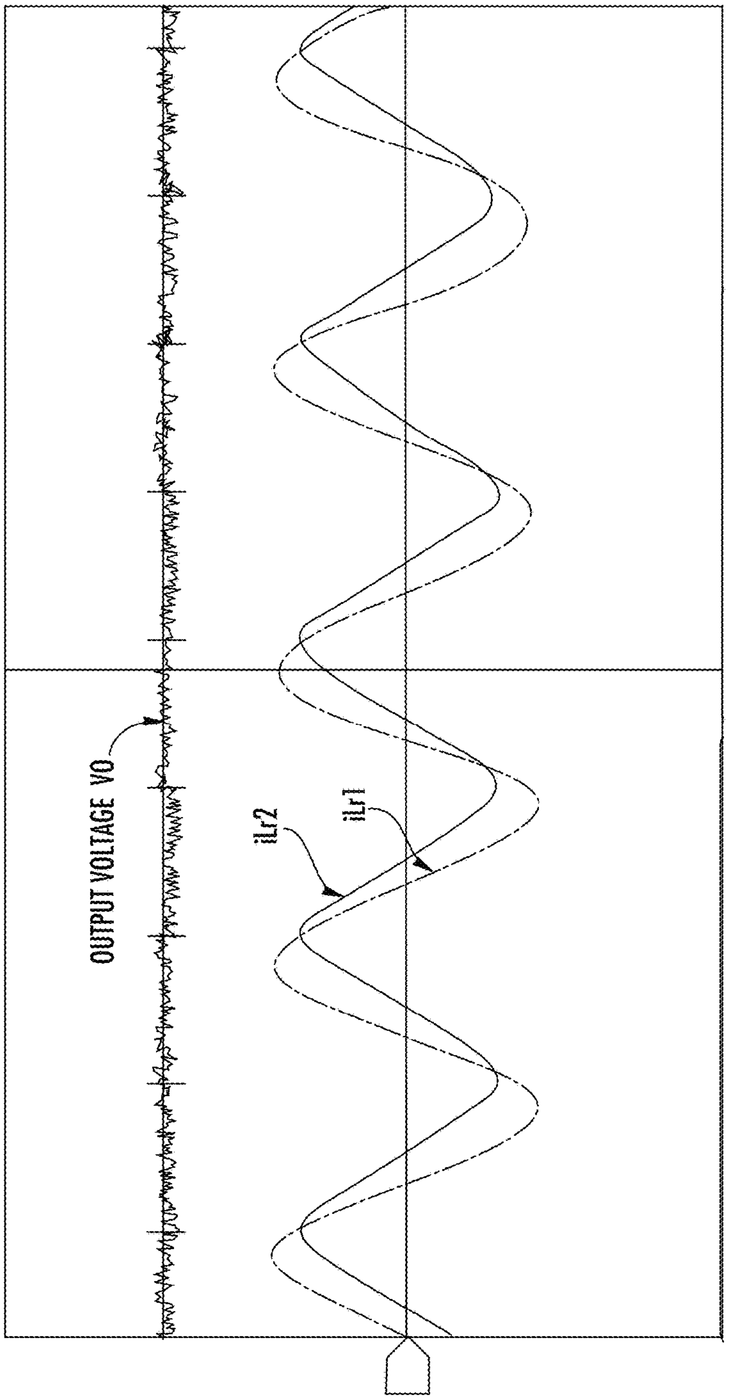

FIG. 14

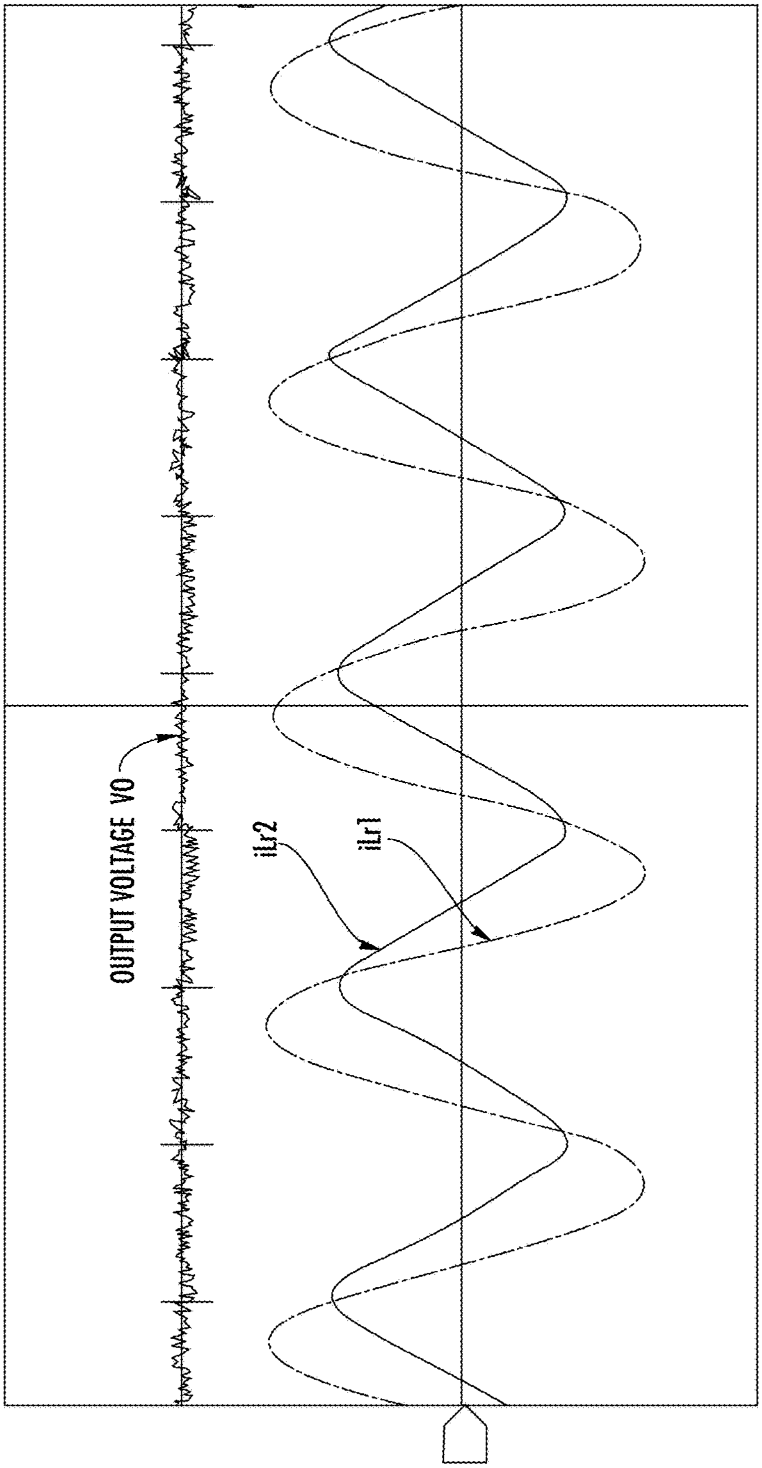

FIG. 15
PRIOR ART

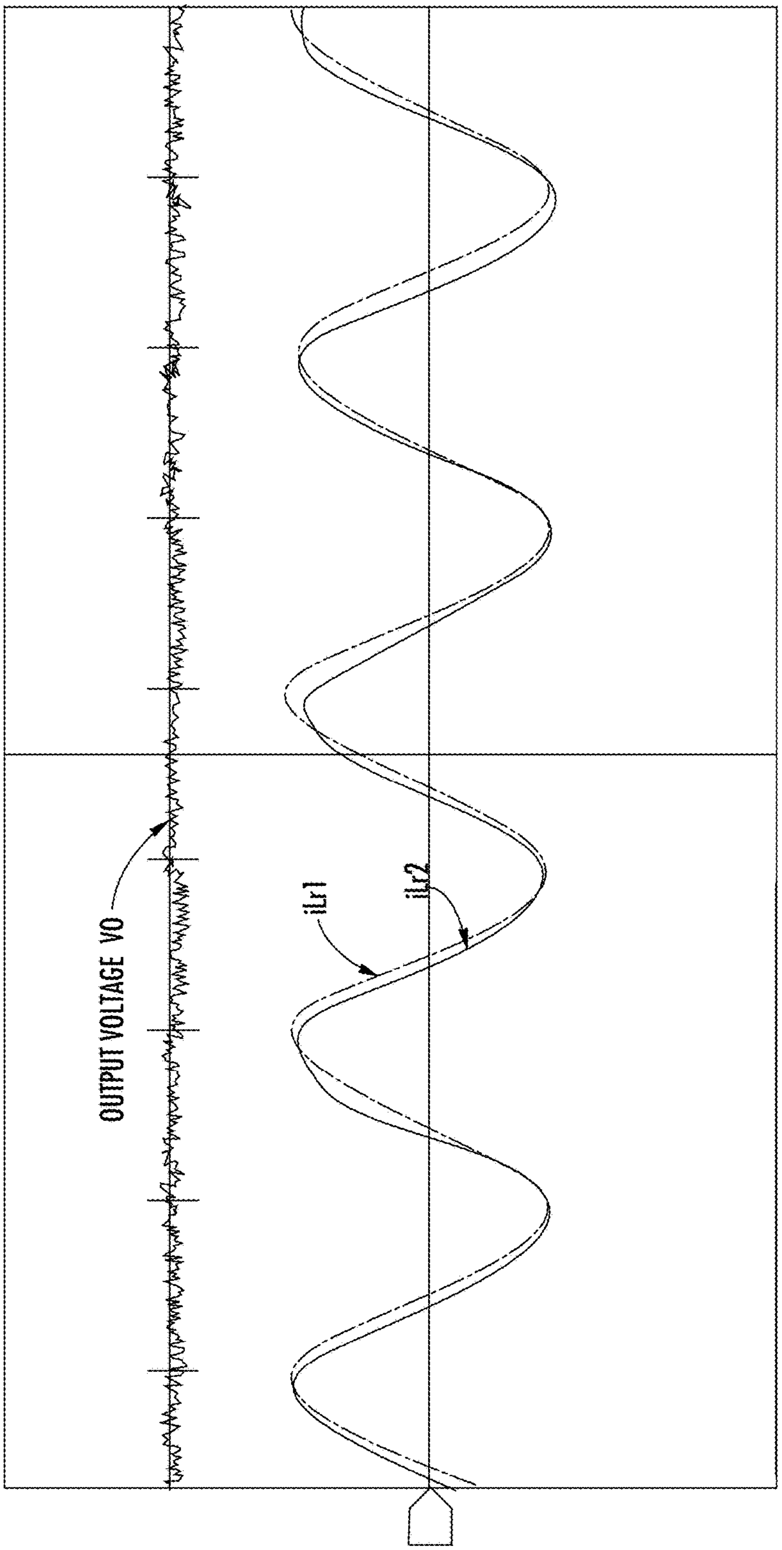

FIG. 16

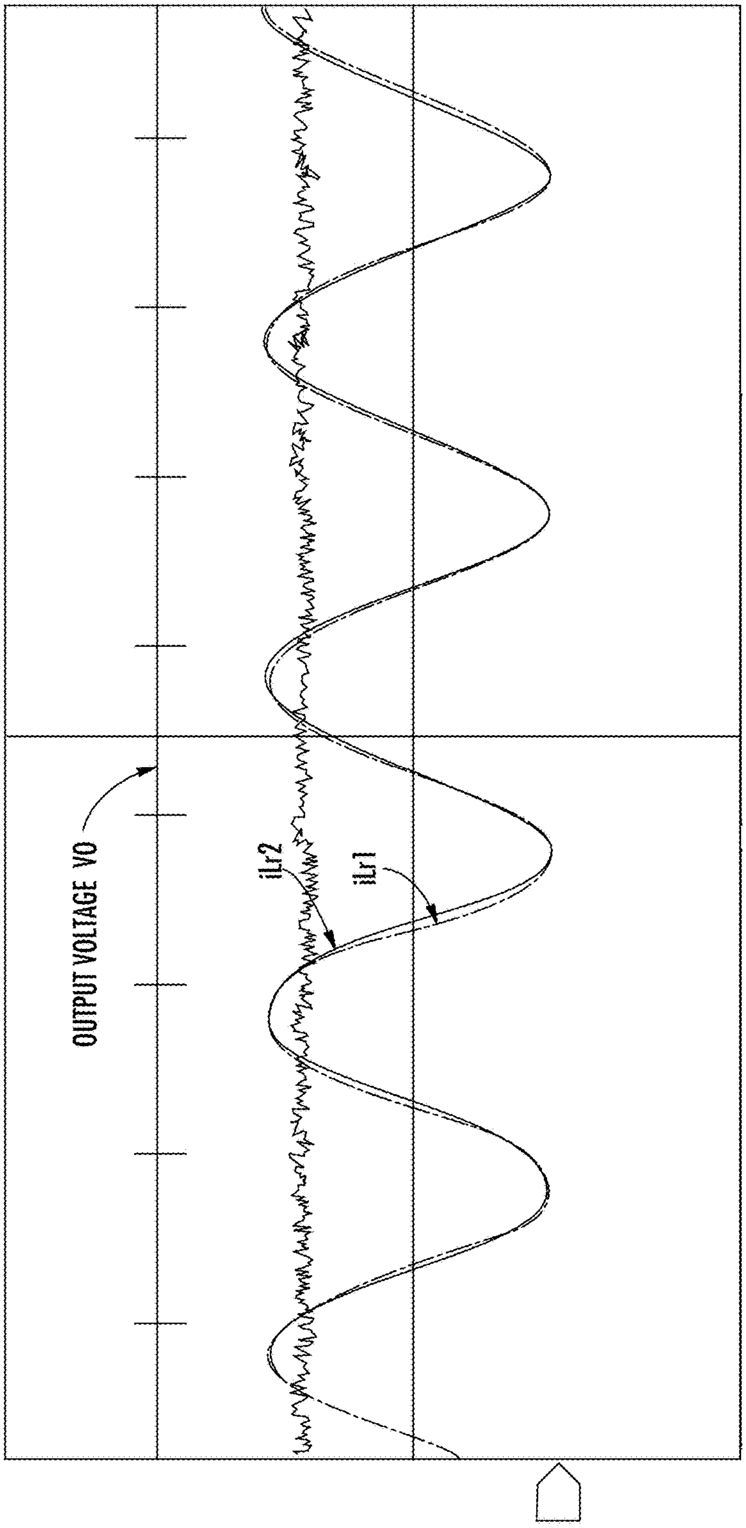

FIG. 17

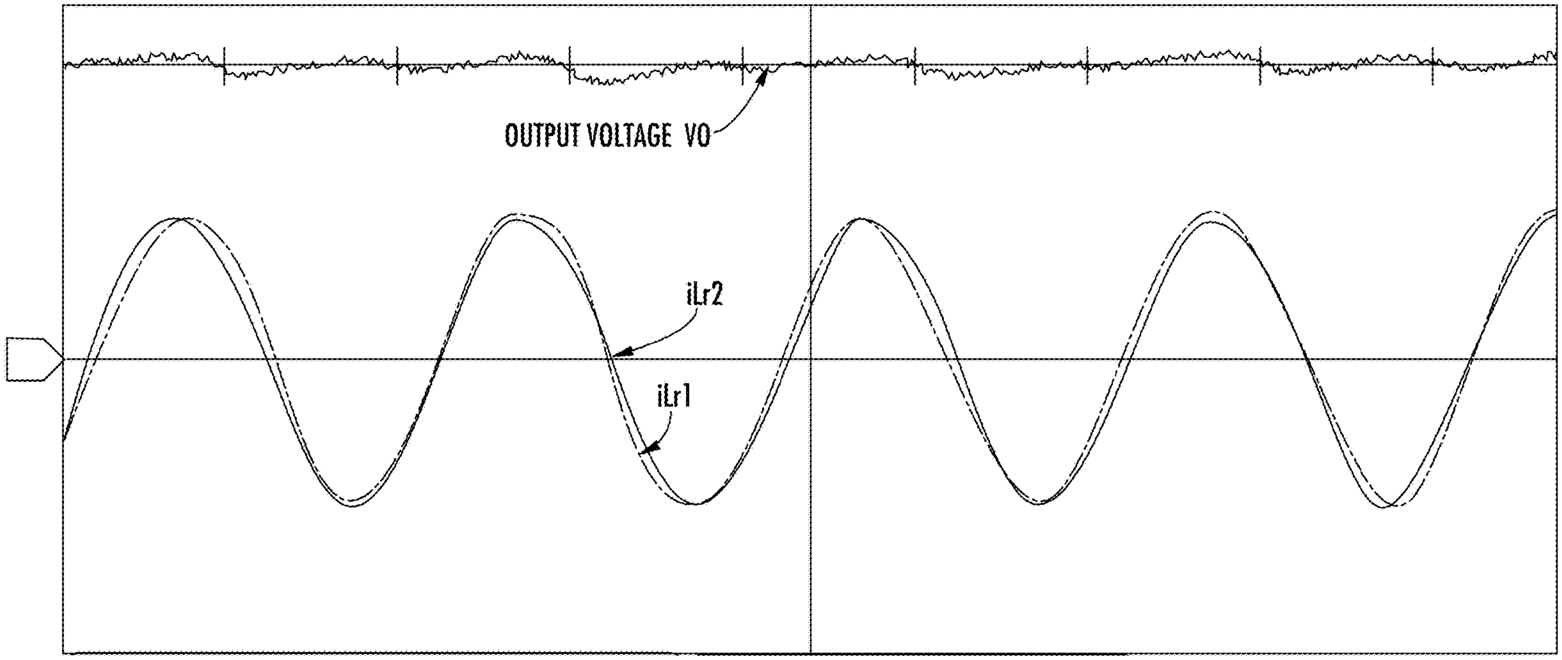

FIG. 18

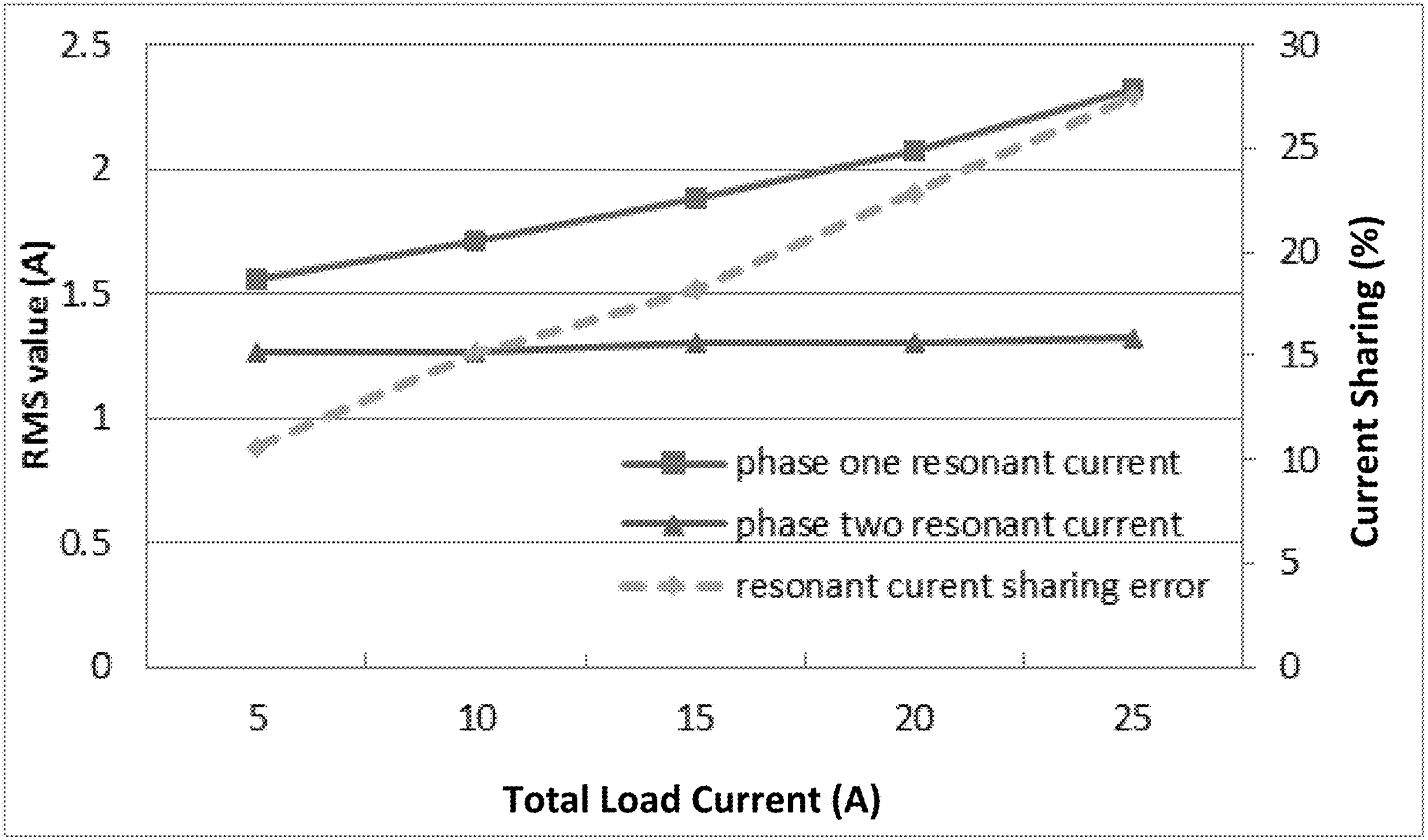

Fig. 19
PRIOR ART

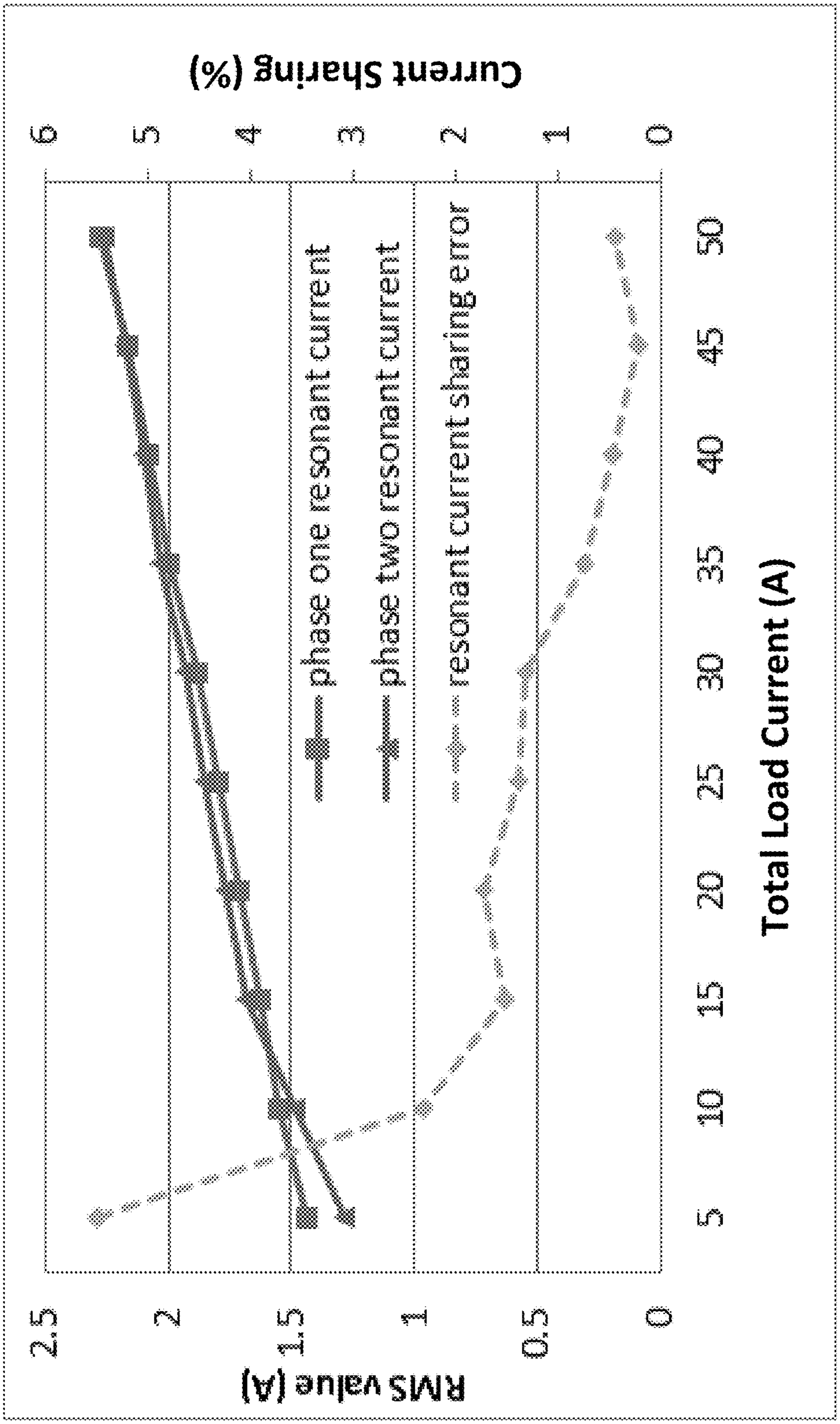
RMS value (A)
2.5
2
1.5
1
0.5
0
Current Sharing (%)
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
50
Total Load Current (A)
phase one resonant current
phase two resonant current
resonant current sharing error

Fig. 20

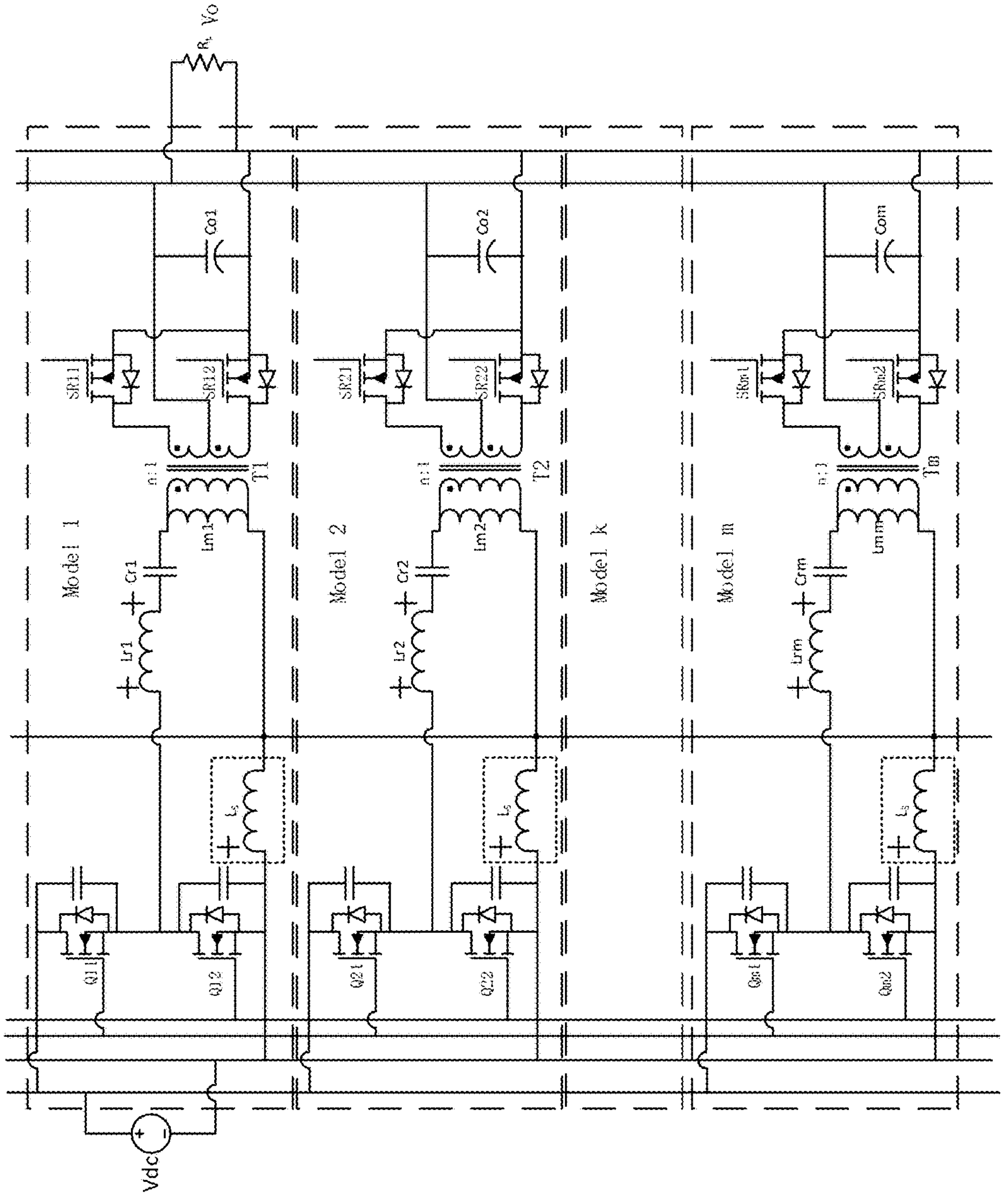
R, Vo
Co1
Co2
Com
SR11
SR12
SR21
SR22
SRm1
SRm2
n:1
n:1
n:1
T1
T2
Tm
Model 1
Model 2
Model k
Model m
Lm1
Lm2
Lmm
Cr1
Cr2
Crm
Lr1
Lr2
Lrm
Ls
Ls
Ls
Q11
Q12
Q21
Q22
Qm1
Qm2
Vdc

Fig. 21

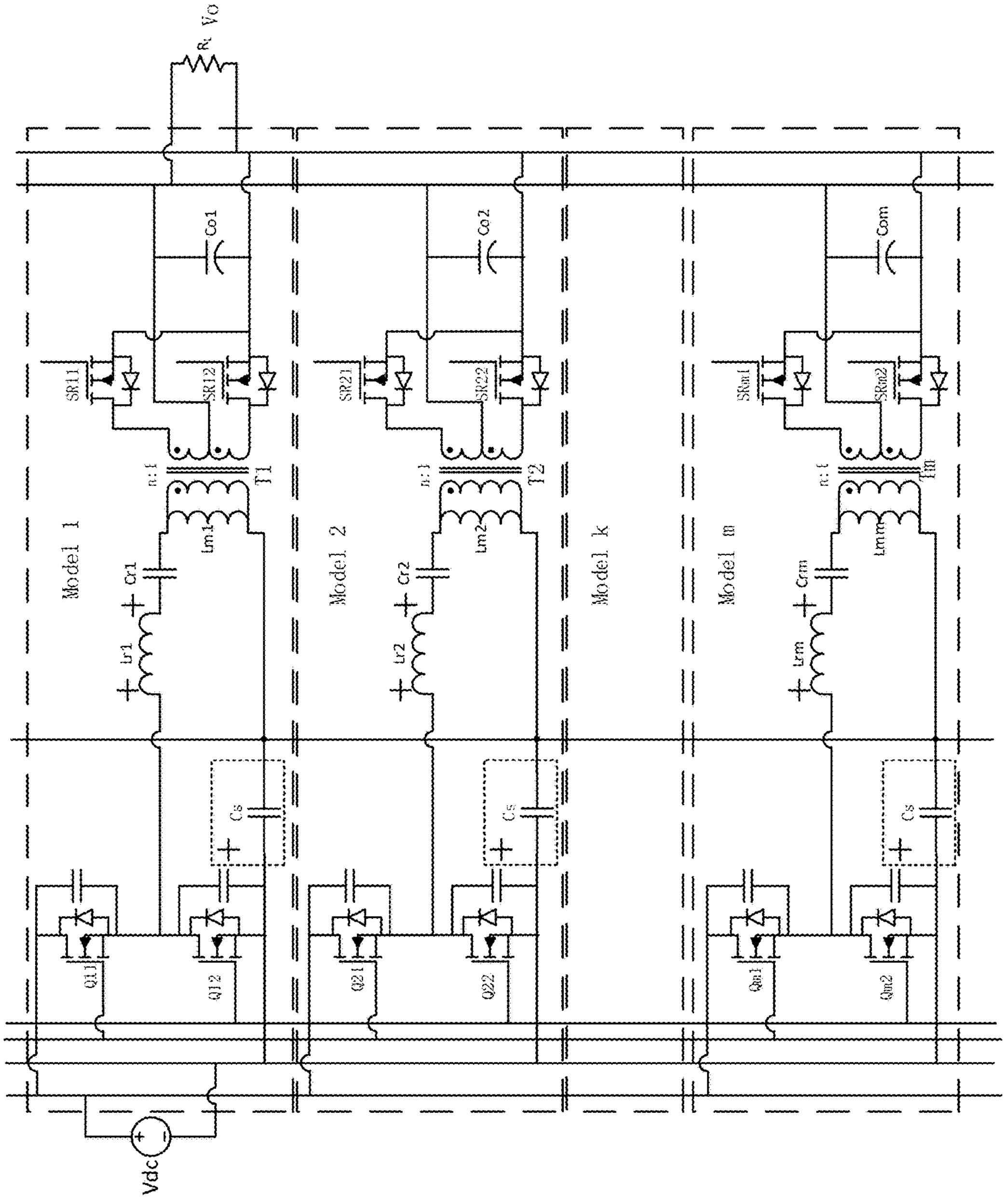
Vo
RL
Co1
Co2
Com
SR11
SR12
SR21
SR22
SRm1
SRm2
n:1
n:1
n:1
T1
T2
Tm
Lm1
Lm2
Lmm
Model 1
Model 2
Model k
Model m
Cr1
Cr2
Crm
Lr1
Lr2
Lrm
Cs
Cs
Cs
Q11
Q12
Q21
Q22
Qm1
Qm2
Vdc

Fig. 22

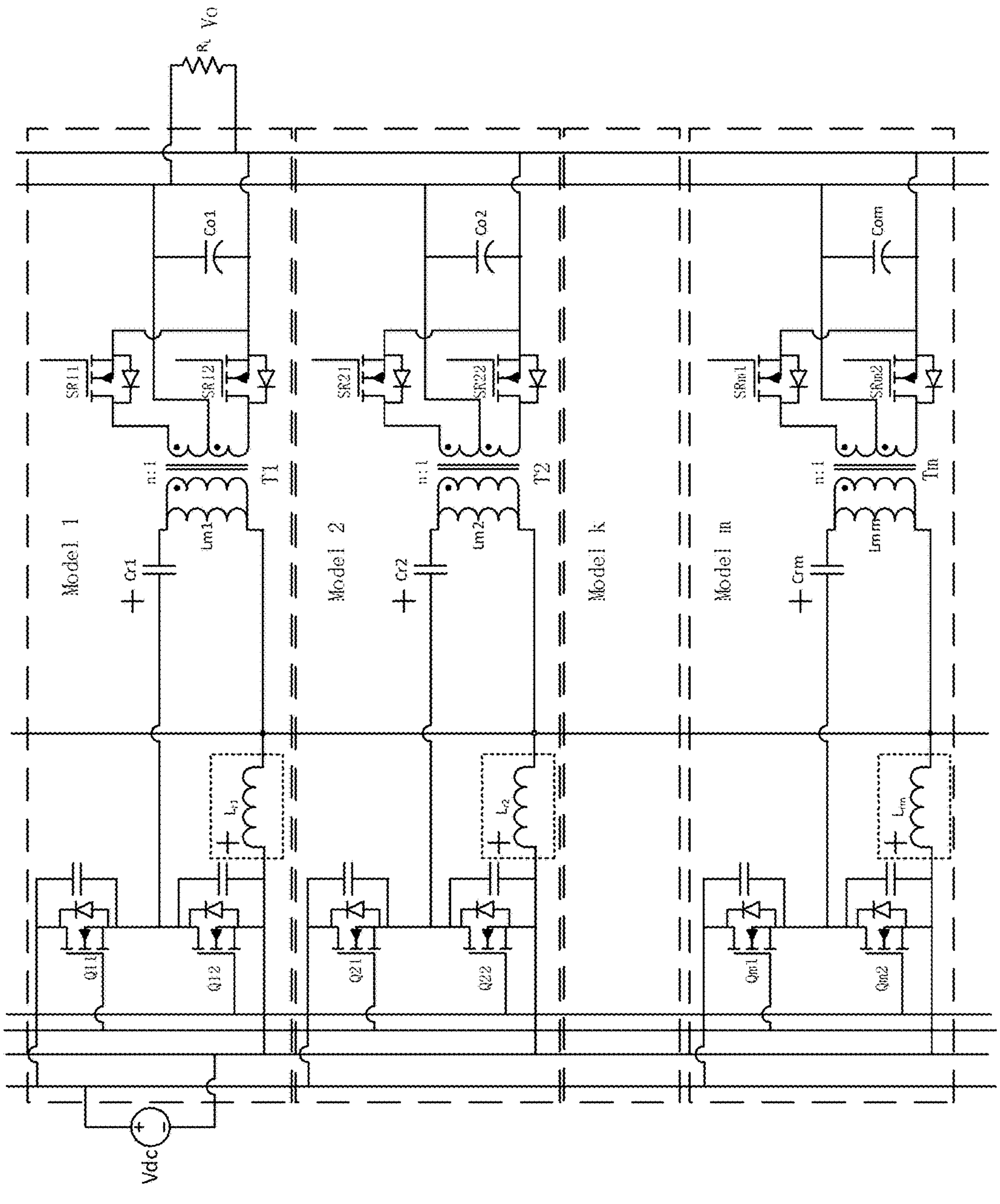
RL
Vo
Co1
Co2
Com
SR11
SR12
SR21
SR22
SRm1
SRm2
n:1
n:1
n:1
T1
T2
Tm
Lm1
Lm2
Lmm
Cr1
Cr2
Crm
Model 1
Model 2
Model k
Model m
Lr1
Lr2
Lrm
Q11
Q12
Q21
Q22
Qm1
Qm2
Vdc

Fig. 23

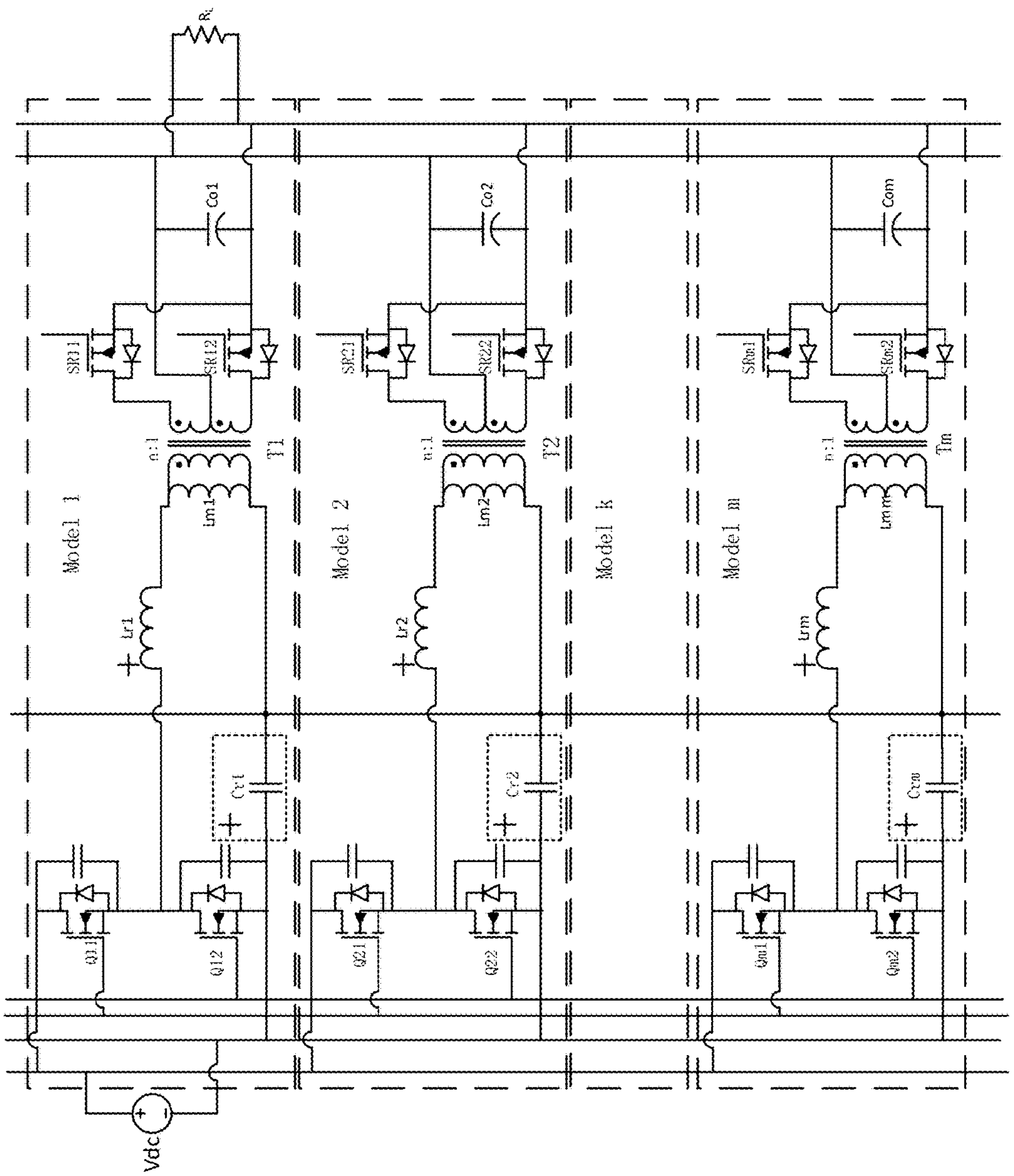
RL
Co1
Co2
Com
SR11
SR12
SR21
SR22
SRm1
SRm2
n:1
n:1
n:1
T1
T2
Tm
Lm1
Lm2
Lmm
Model 1
Model 2
Model k
Model m
Lr1
Lr2
Lrm
Cr1
Cr2
Crm
Q11
Q12
Q21
Q22
Qm1
Qm2
Vdc

Fig. 24

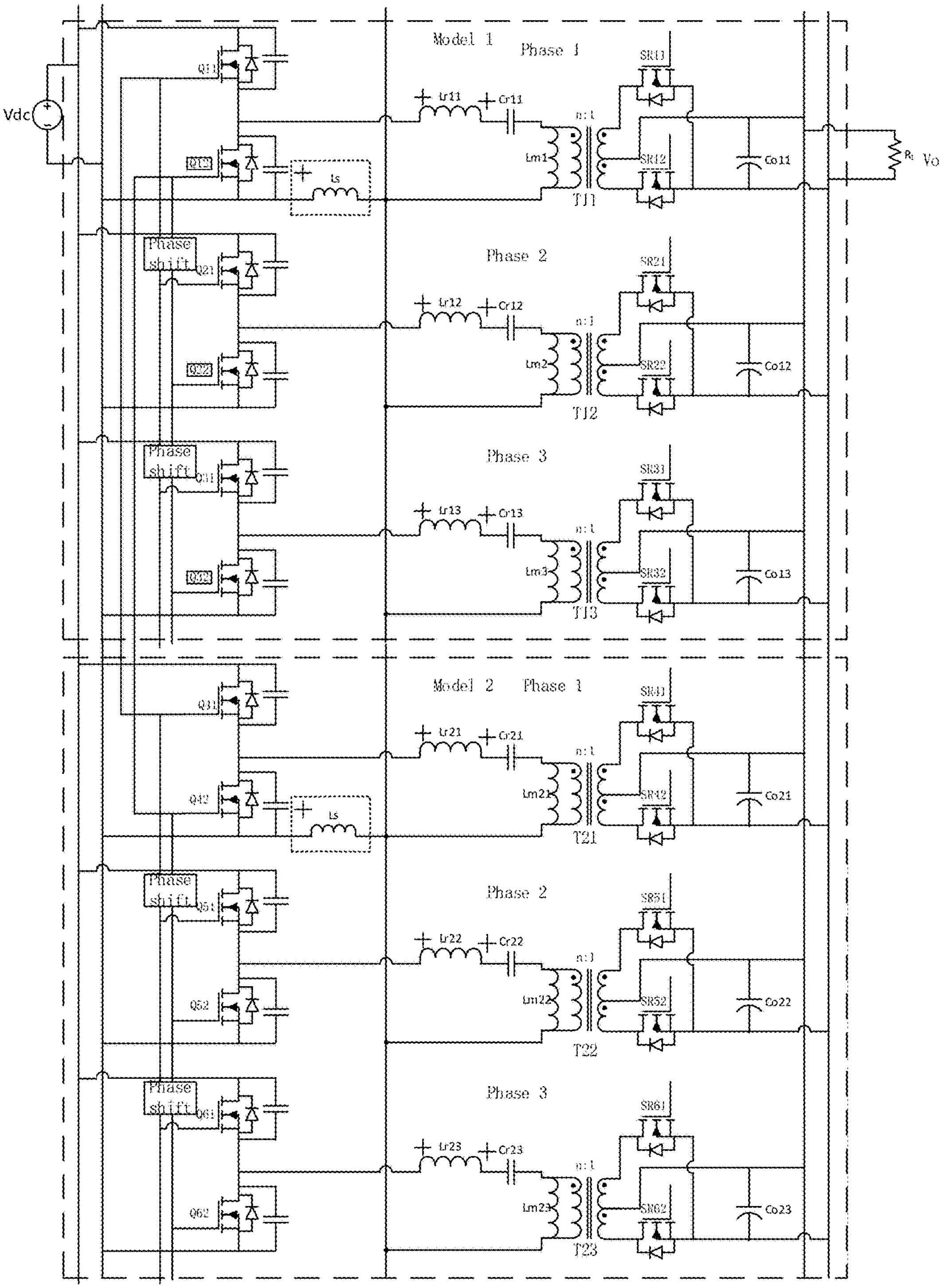
Model 1
Phase 1
Vdc
Q11
Q12
Ls
Lr11
Cr11
n:1
Lm1
T11
SR11
SR12
Co11
Rl
Vo
Phase shift
Q21
Q22
Phase 2
Lr12
Cr12
Lm2
T12
SR21
SR22
Co12
Phase shift
Q31
Q32
Phase 3
Lr13
Cr13
Lm3
T13
SR31
SR32
Co13
Model 2
Phase 1
Q41
Q42
Ls
Lr21
Cr21
Lm21
T21
SR41
SR42
Co21
Phase shift
Q51
Q52
Phase 2
Lr22
Cr22
Lm22
T22
SR51
SR52
Co22
Phase shift
Q61
Q62
Phase 3
Lr23
Cr23
Lm23
T23
SR61
SR62
Co23

Fig. 25

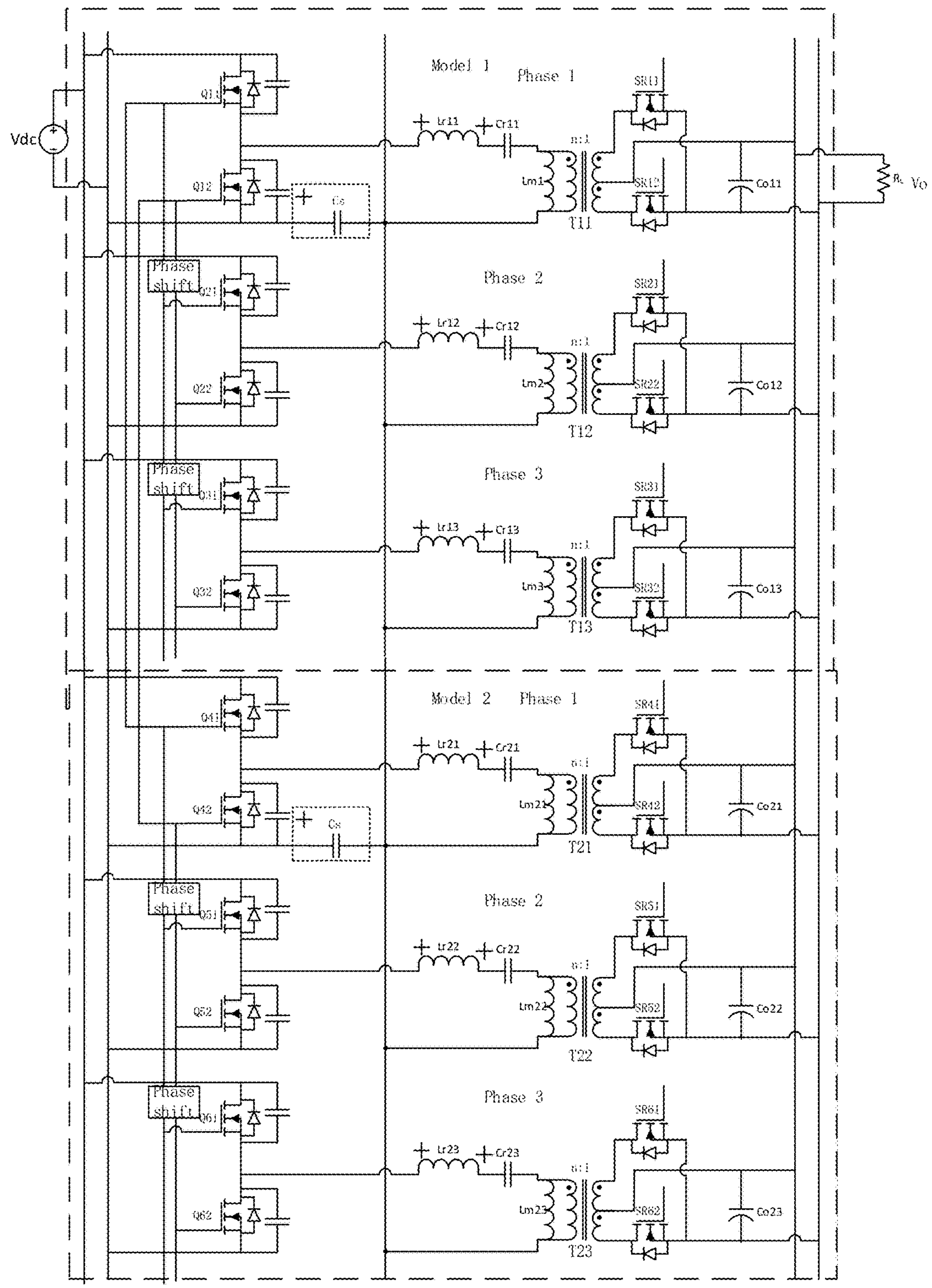
Vdc
Model 1
Phase 1
Q11
Q12
Lr11
Cr11
n:1
Lm1
T11
Cs
SR11
SR12
Co11
RL
Vo
Phase shift
Phase 2
Q21
Q22
Lr12
Cr12
n:1
Lm2
T12
SR21
SR22
Co12
Phase shift
Phase 3
Q31
Q32
Lr13
Cr13
n:1
Lm3
T13
SR31
SR32
Co13
Model 2
Phase 1
Q41
Q42
Lr21
Cr21
n:1
Lm21
T21
Cs
SR41
SR42
Co21
Phase shift
Phase 2
Q51
Q52
Lr22
Cr22
n:1
Lm22
T22
SR51
SR52
Co22
Phase shift
Phase 3
Q61
Q62
Lr23
Cr23
n:1
Lm23
T23
SR61
SR62
Co23

Fig. 26

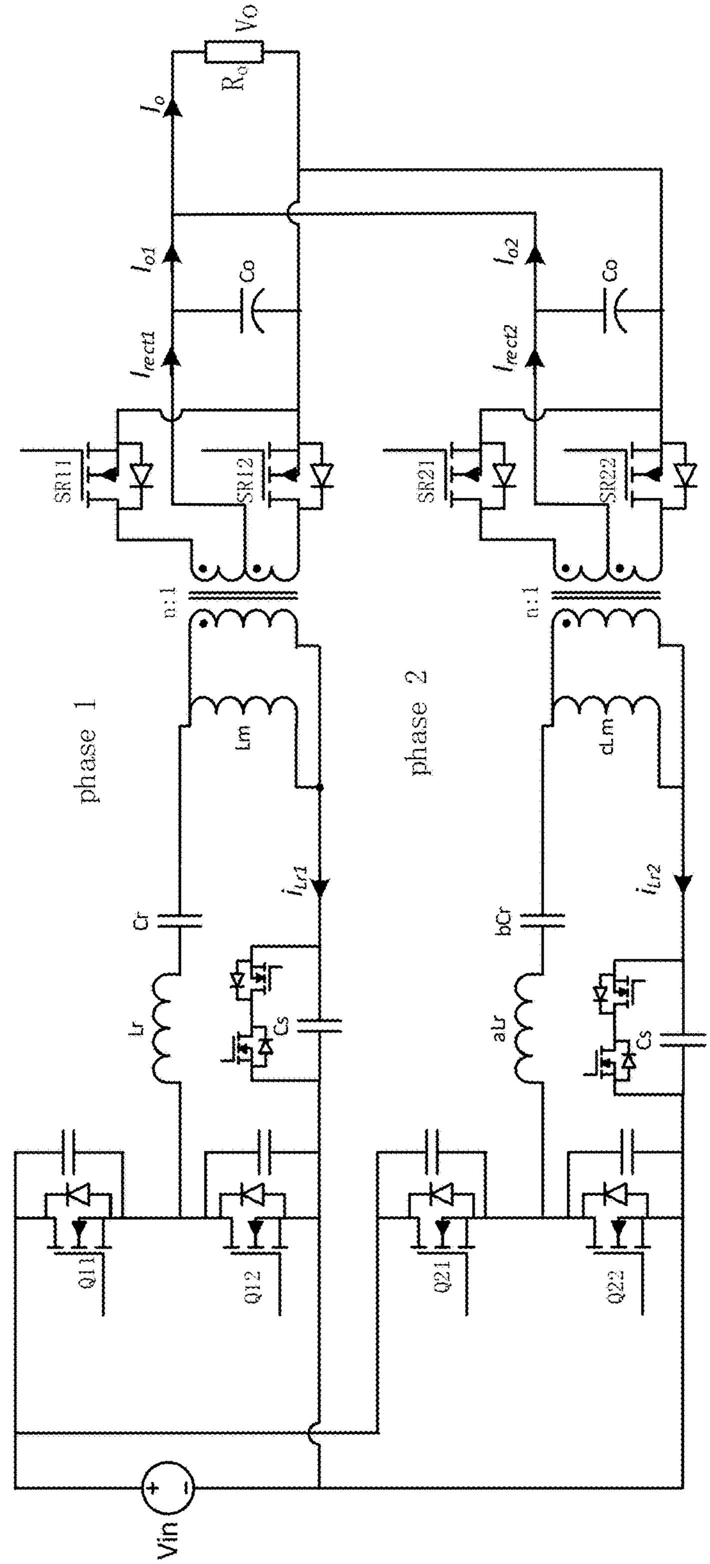

Fig. 27
PRIOR ART

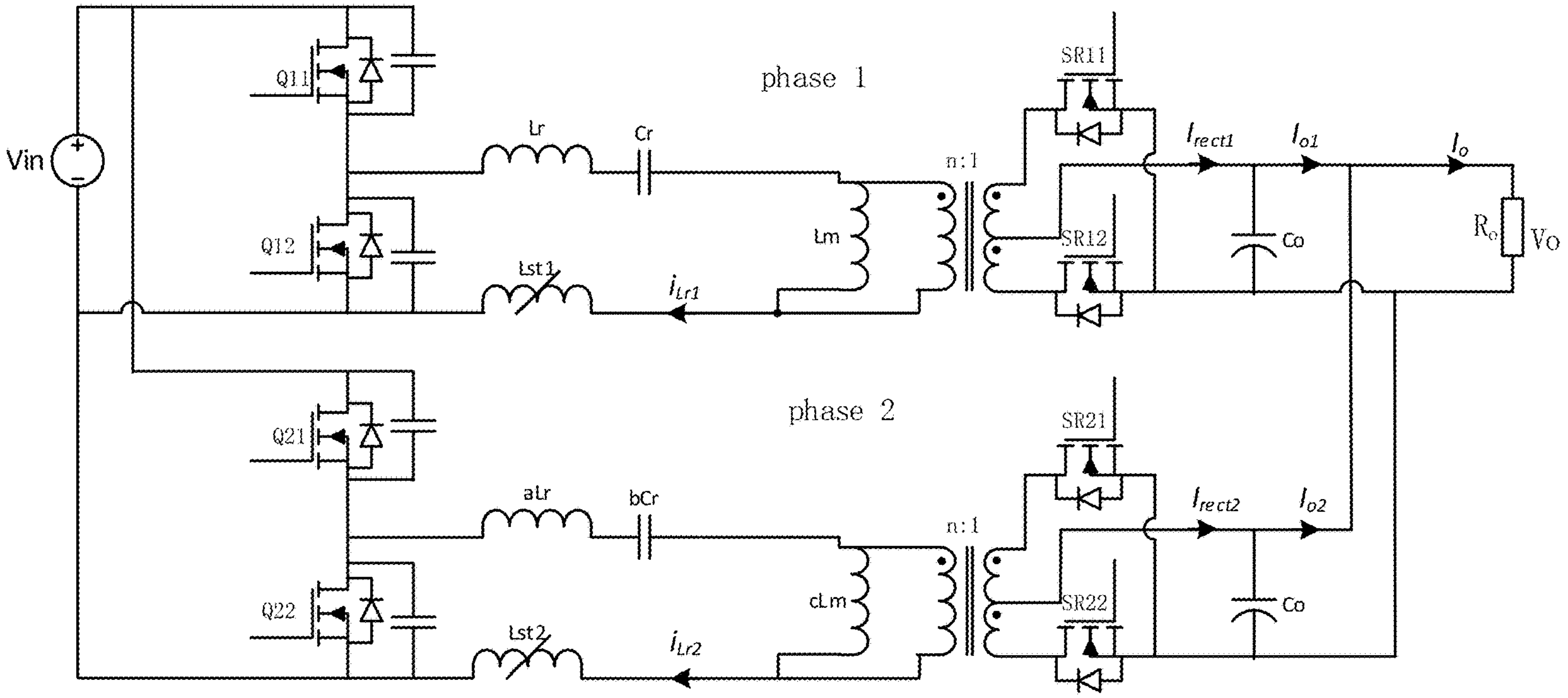

Fig. 28
PRIOR ART

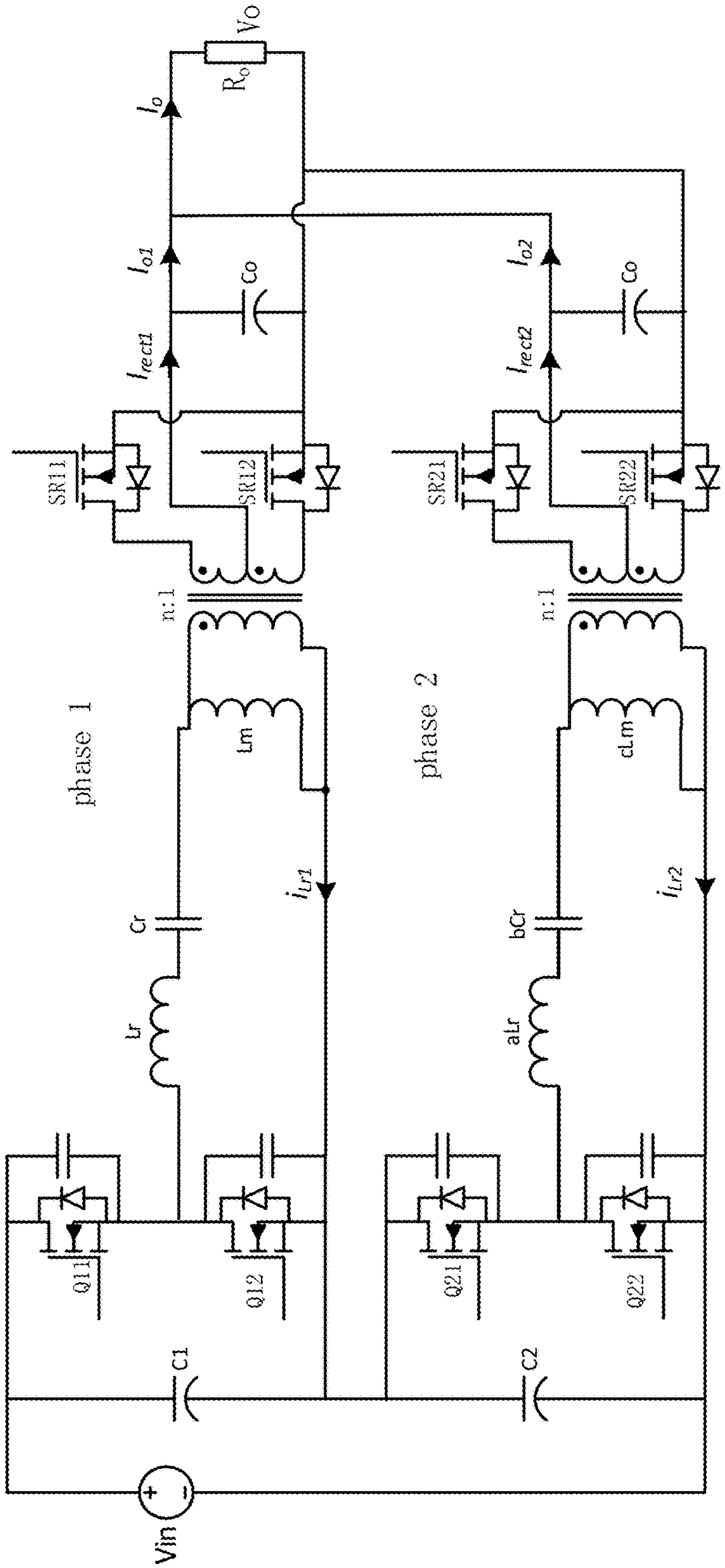

Fig. 29
PRIOR ART

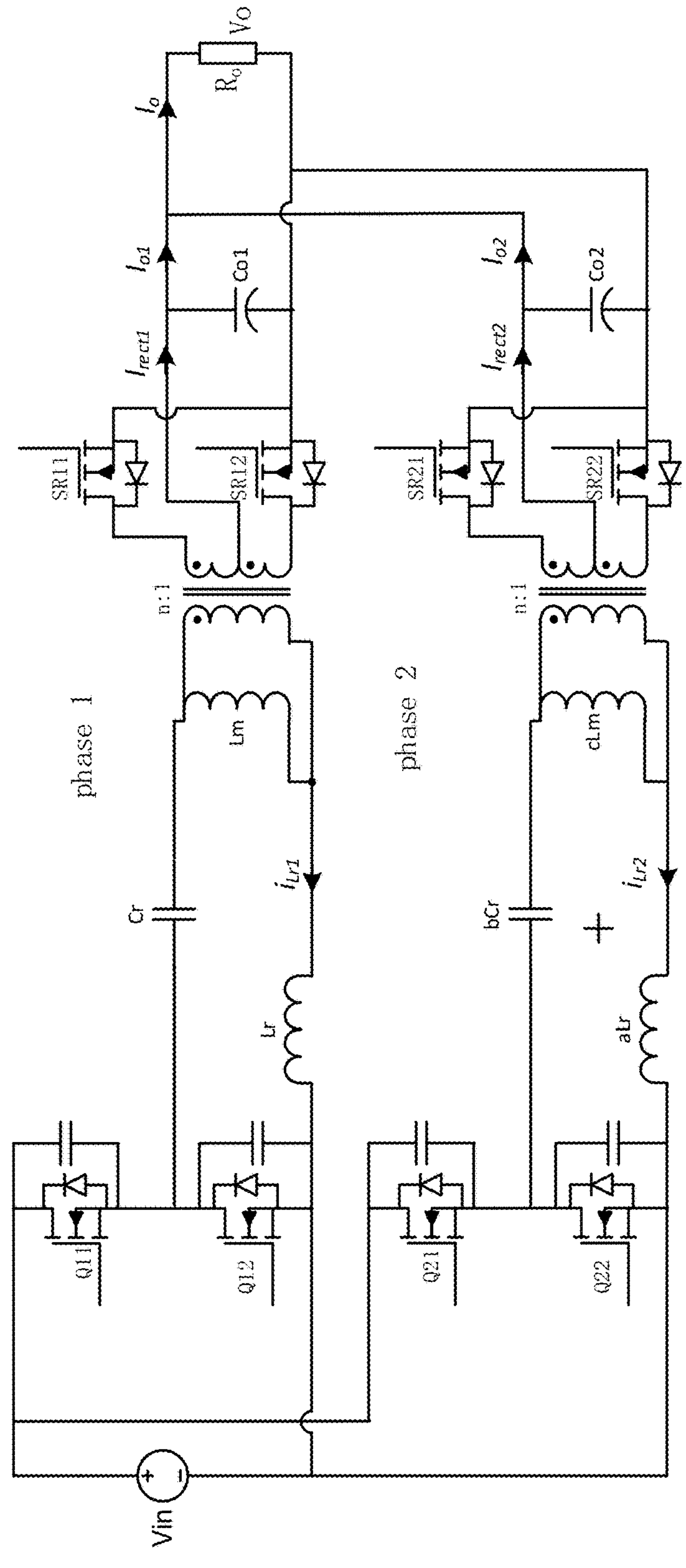

Fig. 30
PRIOR ART

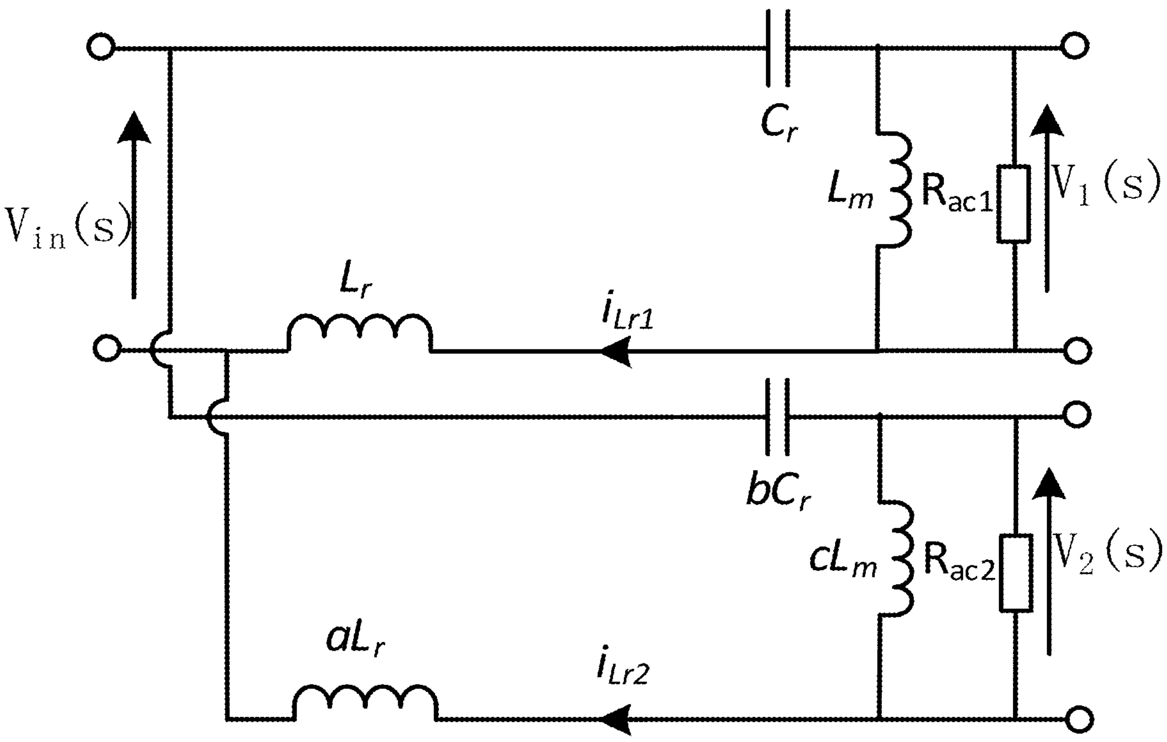

Fig. 31
PRIOR ART

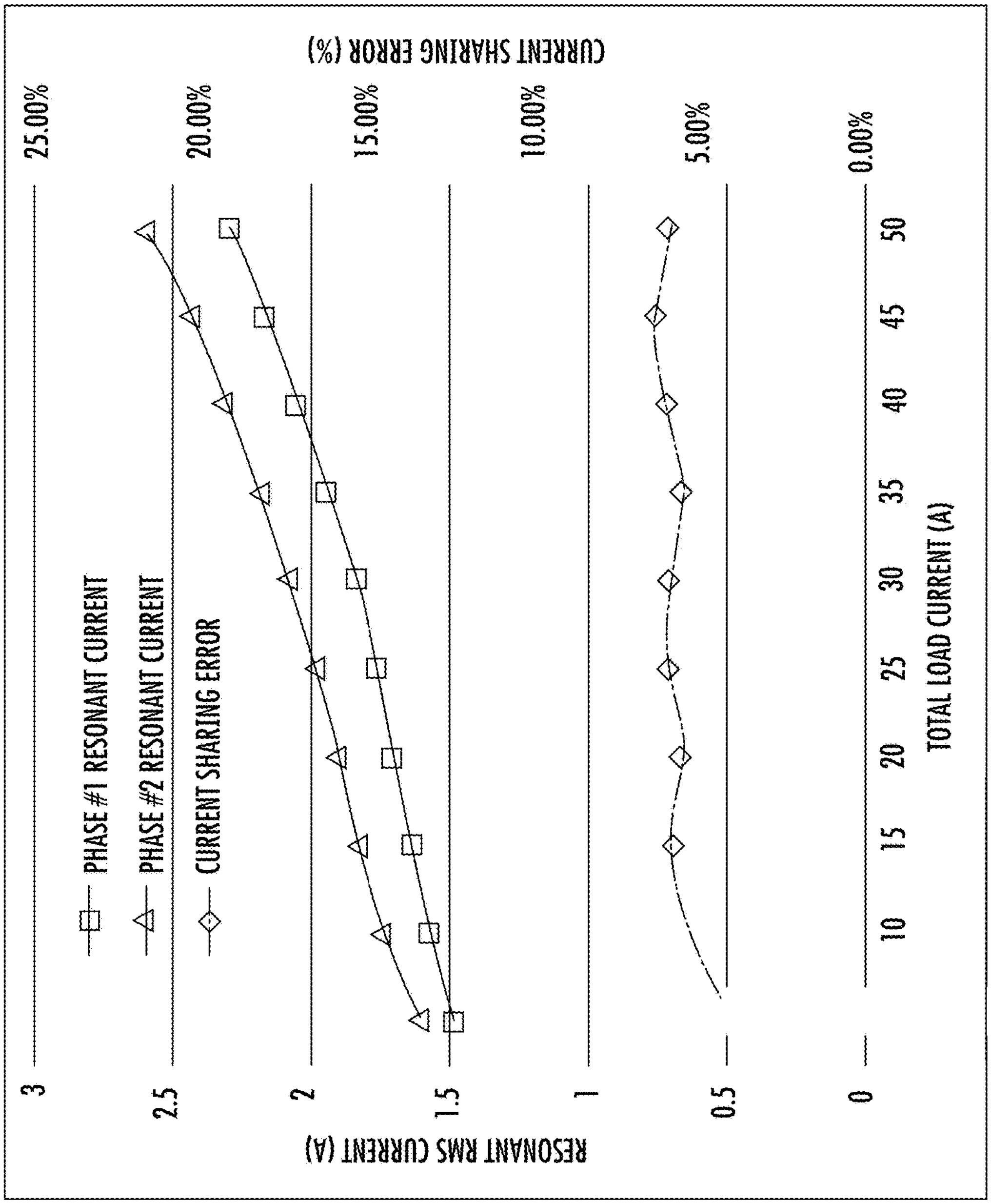
PHASE #1 RESONANT CURRENT
PHASE #2 RESONANT CURRENT
CURRENT SHARING ERROR
RESONANT RMS CURRENT (A)
3
2.5
2
1.5
1
0.5
0
CURRENT SHARING ERROR (%)
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
10
15
20
25
30
35
40
45
50
TOTAL LOAD CURRENT (A)

FIG. 32

MODULAR PARALLEL TECHNIQUE FOR RESONANT CONVERTER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to high-efficiency power supplies and similar devices.

2. Description of the Related Art

A multi-phase, parallel resonant converter is a good choice for high-efficiency, high-power DC/DC applications, such as telecommunication power supplies and similar applications. Load current sharing is a key issue in such applications. Interleaved, parallel power converters can provide an output with a small ripple. However, interleaved, parallel power supplies need additional metal-oxide-semiconductor field-effect transistors (MOSFETs), and therefore, the cost of interleaved, parallel power supplies is higher, and an additional gate-drive circuit is needed. The dynamic performance of interleaved, parallel power is not very good when the load is changing. In particular, at light loads, interleaved, parallel power can be inefficient because of switching losses of all of the MOSFETs.

Known LLC resonant converters are attractive for isolated DC/DC applications, such as flat-panel TVs, laptop adapters, server computers, etc. because of their attractive features: smooth waveforms, high efficiency, and high power density. Known LLC resonant converters have been widely used due to the high efficiency as a result of zero-voltage switching (ZVS) of the primary-side MOSFETs and of zero-current switching (ZCS) of the secondary-side diodes in which the secondary-side diodes are switched between current-flowing and current-blocking states so that the diode current decreases to zero before the next half period. For high-power applications, the current stress on the power devices increases with the power rating. Connecting multiple converters, or phases or stages, in parallel is a good technique to address this problem of current stress. But, because of the tolerances of resonant components, the resonant frequency of each individual converter will be different. Thus, the output currents of the different phases will be different. A small component tolerance, e.g., such as less than 5%, can cause significant current imbalance as shown, for example, in FIG. **4**. Therefore, current sharing is needed to achieve multiphase operation.

FIG. **30** shows a known two-phase converter with phases **1** and **2**. Each phase includes a transformer with primary and secondary windings. The transformer turns ratio is n. A primary circuit is connected to the primary winding, and a secondary circuit is connected to the secondary winding.

The primary circuit of phase **1** includes primary switches Q**11**, Q**12** connected in series and includes resonant inductor Lr, resonant capacitor Cr, and magnetizing inductor Lm connected in series. The magnetizing inductor Lm is connected in parallel with the primary winding. The current i_{Lr1} is the resonant current in phase **1**. The primary circuit of phase **2** includes primary switches Q**21**, Q**22** connected in series and includes resonant inductor aLr, resonant capacitor bCr, and magnetizing inductor cLm connected in series. The values a, b, c indicate that the resonant parameters for these two phases are different. The magnetizing inductor cLm is connected in parallel with the primary winding. The current i_{Lr2} is the resonant current in phase **2**. The primary circuits of phases **1** and **2** are connected to the voltage input Vin.

The secondary circuit of phase **1** includes a rectifying stage including synchronous rectifiers SR**11**, SR**12** connected to the secondary winding and an output capacitor Co**1** connected to the rectifying stage. The current i_{rect1} is the current through the rectifying stage. The current i_{o1} is the load current of phase **1**. The secondary circuit of phase **2** includes a rectifying stage including synchronous rectifiers SR**21**, SR**22** connected to the secondary winding and an output capacitor Co**2** connected to the rectifying stage. The current t_{rect2} is current through the rectifying stage. The current i_{o2} is the load current of phase **2**. The secondary circuits of phases **1** and **2** are connected to the output Vo. The current i_o is the output current. Resistance Ro represents the resistance of the load.

A mathematic model of the LLC converter is needed for analyzing the current sharing characteristics. For simplicity, a two-phase LLC converter without using a sharing method is shown in FIG. **30**. FIG. **31** is the equivalent circuit based on fundamental harmonic analysis (FHA). In steady-state, the load resistor Ro is separated Ro**1** and Ro**2** according to each load current i_{o1}, i_{o2}. The primary-side equivalent ac resistors Rac**1**, Rac**2** are:

$$\begin{cases} R_{o1} = \frac{1}{k}R_o,\ R_{o2} = \frac{1}{(1-k)}R_o,\ k \in [0, 1] \\ R_{ac} = \frac{8n^2}{\pi^2}R_o,\ R_{ac1} = \frac{8n^2}{\pi^2}R_{o1},\ R_{ac2} = \frac{8n^2}{\pi^2}R_{o2} \end{cases} \tag{1}$$

where k is the impedance sharing error that is between **0** and **1**. If k=0.5, then the load power is equally shared by the two phases. If k=0 or 1, then the load power can only be provided by one of the phases.

Three known current-sharing methods have been used with multiphase LLC converters. The first known current-sharing method is the active method which adjusts the equivalent resonant capacitor or inductor to compensate for the components' tolerances using additional MOSFETs as shown in FIGS. **27** and **28**. This method can achieve excellent load-sharing performance. An example of this known method using a switched capacitor is shown in FIG. **27**.

The known current-sharing method using switched capacitors shown in FIG. **27**. Each phase has a switched capacitor. The switched capacitor includes the capacitor Cs with two transistors connected in series with each other and connected in parallel across the capacitor Cs. The two transistors define an additional switch that charges or discharges the capacitor Cs. The equivalent capacitor is a variable capacitor with a changing duty ratio.

The known current-sharing method using a variable inductor is shown in FIG. **28**. The converter in FIG. **28** is similar to the converter in FIG. **27**, except that the switched capacitor is replaced with variable inductors Lst**1**, Lst**2**. The variable inductors Lst**1**, Lst**2** include an extra circuit with additional switches that control the coupled windings of the variable inductors Lst**1**, Lst**2**.

This known current-sharing method uses an additional circuit, which includes switches, a passive element such as a capacitor or an inductor, and a detecting current circuit. The circulated current can be controlled by changing the resonant frequency based on the additional circuit. The equivalent resonant inductance or capacitance is changed by the variable inductor or the switched capacitor in the additional circuit. Thus, the resonant frequency is changed as the inductance or capacitance is changed. These known current-sharing methods with the switched capacitor and the variable inductor suffer from high cost, complex control, and inferior dynamic performance because of the required sensing circuit and of the need to control the additional switches.

A second known current-sharing method is the DC-voltage, self-balanced method that uses series DC-bus capacitors as shown in FIG. **29**. The series DC-bus capacitors of the two-phase converter shown in FIG. **29** includes two capacitors C**1**, C**2** connected in series, which can share the current by automatically adjusting the voltage of the two series capacitors C**1**, C**2**. Capacitor C**1** is connected in parallel across primary switches Q**11**, Q**12**, and capacitor C**2** is connected in parallel across primary switches Q**21**, Q**22**. The two large series DC capacitors C**1**, C**2** are connected in series to share the input DC voltage. FIG. **29** shows a two-phase LLC converter to explain the principle. The mid-point voltage is changed according to the power of the two phases. The input voltage of the first module is the voltage of the capacitor C**1**, and the input voltage of the second module is the voltage of the capacitor C**2**. The input voltage of each module can be changed to balance power by the series DC capacitor. The output voltage is same for each of the modules; thus, the current can be shared. Thus, the converter has low cost and good load-current sharing performance.

To balance the capacitor voltage, it is better to use a two-phase LLC converter. It is difficult to use additional modules. It is hard to achieve a modular design with the second known current-sharing method because the DC voltage stress is reduced as the number of modules increases. The total input voltage and output voltage is constant. When two modules are used in the series DC capacitor current-sharing method, the input voltage of each of the modules is about half of the total input voltage. When three modules are used, the input voltage of each module is about a third of the total input voltage. When the input voltage is low, the design of the LLC converter will not be optimized because the resonant current (i.e., the input current) will be increased. In addition, when one module fails, the input voltage for the other modules will have a large change, which is not desirable.

A third known current-sharing method is based on a three-phase, three-wire structure for three-phase LLC converters based on a 120°-phase-shift method, which has good load-current sharing near the resonant frequency as all of the three-phase resonant currents are zero. But this third known current-sharing method is only suitable for three LLC converter phases connected in parallel. The load current will not share with more than three phases.

Therefore, the known current-sharing methods do not provide cost effective, flexible current sharing for multi-phase LLC resonant converters.

SUMMARY OF THE INVENTION

To overcome the problems described above, preferred embodiments of the present invention provide an improved LLC resonant converter and method that makes it possible to automatically share the load current without additional cost and without additional control. Preferred embodiments of the present invention provide a common-inductor, multi-phase LLC resonant converter that achieves automatic load sharing. The resonant inductor in each phase is connected in parallel, which allows the automatic load-current sharing. The topology of the preferred embodiments of the present invention is simple, and no additional cost and complex control method are needed. The common-inductor current sharing method can be expanded to any number of phases.

According to a preferred embodiment of the present invention, an LLC resonant converter includes a voltage input, a voltage output, a first phase, and a second phase. The first phase includes a first transformer with first primary and first secondary windings, a first primary circuit connected to the voltage input and the first primary winding, and a first secondary circuit connected to the first secondary winding and the voltage output. The first primary circuit includes a first resonant capacitor, a first magnetizing inductor connected in parallel across the first primary winding, and a first resonant inductor. The first resonant capacitor, the first magnetizing inductor, and the first resonant inductor are connected in series. The first secondary circuit includes a first rectifying circuit. The second phase includes a second transformer with second primary and second secondary windings, a second primary circuit connected to the voltage input and the second primary winding, and a second secondary circuit connected to the second secondary winding and the voltage output. The second primary circuit includes a second resonant capacitor, a second magnetizing inductor connected in parallel across the second primary winding, and a second resonant inductor. The second resonant capacitor, the second magnetizing inductor, and the second resonant inductor are connected in series. The second secondary circuit includes a second rectifying circuit. The first primary circuit includes a first shared inductor, and the second primary circuit includes a second shared inductor. The first and second shared inductors are connected in parallel with each other. The first and second primary circuits do not include a capacitor that is connected in parallel with each other.

The first and second rectifying circuits preferably include synchronous rectifiers. Preferably, the first phase includes a first output capacitor, and the second phase includes a second output capacitor. Preferably, the LLC resonant converter further includes at least one additional phase including at least one additional shared inductor, and the at least one additional shared inductor is connected in parallel with the first and second shared inductors.

Preferably, the first shared inductor includes first and second ends, the second shared inductor includes first and second ends, the first ends of the first and second shared inductors are directly connected to each other, and the second ends of the first and second shared inductors are directly connected to each other.

Preferably, the first shared inductor is the first resonant inductor, and the second shared inductor is the second resonant inductor.

The above and other features, elements, characteristics, steps, and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments of the present invention with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a two-phase LLC resonant converter with current sharing according to a first preferred embodiment of the present invention.

FIG. **2** shows an FHA equivalent circuit of the converter shown in FIG. **1**.

FIGS. **3-5** show load current sharing error for the known converter shown in FIG. **30**.

FIGS. **6-8** show load current sharing error for the converter shown in FIG. **1**.

FIGS. **9** and **10** show waveforms of the known converter shown in FIG. **30**.

FIGS. **11**-**13** show waveforms of the converter shown in FIG. **1**.

FIGS. **14** and **15** show waveforms of the known converter shown in FIG. **30**.

FIGS. **16**-**18** show waveforms of the converter shown in FIG. **1**.

FIG. **19** shows the resonant currents of the known converter shown in FIG. **30**.

FIG. **20** shows the resonant currents of the converter shown in FIG. **1**.

FIG. **21** is a circuit diagram of a modular parallel converter with a shared inductor.

FIG. **22** is a circuit diagram of a modular parallel converter with a shared capacitor.

FIG. **23** is a circuit diagram of a specific example of FIG. **21**.

FIG. **24** is a circuit diagram of a specific example of FIG. **22**.

FIG. **25** shows two modular parallel three-phase converters with a shared inductor.

FIG. **26** shows two modular parallel three-phase converters with a shared capacitor.

FIG. **27**-**29** show converters using known current-sharing methods.

FIG. **30** shows a known two-phase LLC resonant converter.

FIG. **31** shows an FHA equivalent circuit of the converter shown in FIG. **30**.

FIG. **32** shows the resonant currents of a two-phase converter using a common-capacitor current-sharing method.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the common-inductor current-sharing method for multi-phase LLC resonant converter of the preferred embodiments of the present invention, the series resonant inductors in each phase are connected in parallel. No additional components are needed to achieve current sharing. Analysis of the common-inductor current-sharing method shows that the relative resonant current is significantly reduced. Simulated and experimental results show that the resonant current error is reduced by 63 times and is only 0.44% at 600 W total load power. As a comparative example, a common-capacitor current-sharing method is also discussed. The common-capacitor current-sharing method is only able to achieve a resonant current error of 5% at 600 W total load power as shown in FIG. **32**. The LLC resonant converter shown in FIG. **30** can only achieve a resonant current error of 27% at 600 W total load power.

FIG. **1** shows a two-phase LLC resonant converter using the common-inductor current-sharing method. FIG. **2** shows the FHA equivalent circuit. The converter includes phases **1** and **2**. Each phase includes a transformer with primary and secondary windings. The transformer turns ratio is n. A primary circuit is connected to the primary winding, and a secondary circuit is connected to the secondary winding.

The primary circuit of phase **1** includes primary switches Q**11**, Q**12** connected in series and includes resonant inductor Lr, resonant capacitor Cr, and magnetizing inductor Lm connected in series. The magnetizing inductor Lm is connected in parallel with the primary winding. The current i_{Lr1} is the resonant current in phase **1**. The primary circuit of phase **2** includes primary switches Q**21**, Q**22** connected in series and includes resonant inductor aLr, resonant capacitor bCr, and magnetizing inductor cLm connected in series. The values a, b, c indicate that the resonant parameters for these two phases are different. The magnetizing inductor cLm is connected in parallel with the primary winding. The current i_{Lr2} is the resonant current in phase **2**. The primary circuits of phases **1** and **2** are connected to the voltage input Vin.

The secondary circuit of phase **1** includes a rectifying stage including synchronous rectifiers SR**11**, SR**12** connected to the secondary winding and an output capacitor Co**1** connected to the rectifying stage. The current i_{rect1} is the current through the rectifying stage. The current i_{o1} is the load current of phase **1**. The secondary circuit of phase **2** includes a rectifying stage including synchronous rectifiers SR**21**, SR**22** connected to the secondary winding and an output capacitor Co2 connected to the rectifying stage. It is possible to use passive diodes instead of active synchronous rectifiers SR**21**, SR**22** to provide a rectified output. The current i_{rect2} is the current through the rectifying stage. The current i_{o2} is the load current of phase **2**. The secondary circuits of phases **1** and **2** are connected to the output Vo. The current i_o is the output current. Resistance Ro represents the resistance of the load.

In FIG. **1**, the resonant inductors Lr and aLr of the two phases are connected together according to the common-inductor current-sharing method of the preferred embodiments of the present invention. Terminals of the resonant inductors Lr and aLr are directly connected to each other. The resonant capacitors Cr and bCr are not directly connected to each other. The AC voltage angles are always different because of the tolerances in the resonant components. The relationship between the transfer functions is:

$$|V_1(s)|=|V_2(s)| \tag{2}$$

According to FIG. **31**, the transfer functions $V_1(s)$, $V_2(s)$ are provided by:

$$\begin{cases} V_1(s) = \dfrac{R_{ac1} \,//\, sL_m}{R_{ac1} \,//\, sL_m + sL_r + 1/sC_r} V_{in}(s) \\ V_2(s) = \dfrac{R_{ac2} \,//\, scL_m}{R_{ac2} \,//\, scL_m + saL_r + 1/sbC_r} V_{in}(s) \end{cases} \tag{3}$$

According to the FIG. **5**, the transfer functions $V_1(s)$, $V_2(s)$ are provided by:

$$\begin{cases} V_1(s) = \dfrac{R_{ac1} \,//\, sL_m}{R_{ac1} \,//\, sL_m + 1/sC_r} (V_{in}(s) + V_{Lr}(s)) \\ V_2(s) = \dfrac{R_{ac2} \,//\, scL_m}{R_{ac2} \,//\, scL_m + 1/sbC_r} (V_{in}(s) + V_{Lr}(s)) \end{cases} \tag{4}$$

According to equations (1) and (2) and either (3) or (4), the follow relationship is found:

$$Ak^2+Bk+C=0 \tag{5}$$

For a two-phase LLC resonant converter according to the first preferred embodiment of the present invention, the parameters A, B, C are provided by:

$$\begin{cases} A = \omega^2(1-b^2)c^2L_m^2 - \omega^4(2ab-2b^2)c^2L_rL_m^2C_r + \\ \quad \omega^6(a^2-1)b^2c^2L_r^2L_m^2C_r^2 \\ B = -2\omega^2c^2L_m^2 + 4\omega^4abc^2L_rL_m^2C_r - 2\omega^6a^2b^2c^2L_r^2L_m^2C_r^2 \\ C = \omega^2c^2L_m^2 - 2\omega^4abc^2L_rL_m^2C_r + \omega^6a^2b^2c^2L_r^2L_m^2C_r^2 + \\ \quad (1-b^2c^2)R_{ac}^2 - \omega^2[(2ab-2b^2c^2)L_r + (2bc-2b^2c^2)L_m]C_rR_{ac} + \\ \quad \omega^4(ab-bc)[(ab+bc)L_r^2 + 2bcL_rL_m]C_r^2R_{ac}^2 \end{cases} \tag{6}$$

where $\omega=2\pi f_s$ and f_s is switching frequency.

For a two-phase known LLC converter as shown in FIG. **30**, the parameters A, B, C are provided by:

$$\begin{cases} A = \omega^2(1-b^2)c^2L_m^2 \\ B = -2\omega^2c^2L_m^2 \\ C = \omega^2c^2L_m^2 + (1-b^2c^2)R^2 - 2\omega^2(bc-b^2c^2)L_{in}C_rR_{ac}^2 \end{cases} \tag{7}$$

The current sharing error k is provided by:

$$k = \begin{cases} -\frac{C}{B} & A = 0,\ B \neq 0 \\ \frac{-B \pm \sqrt{B^2-4AC}}{2A} & A \neq 0,\ \sqrt{B^2-4AC} \geq 0 \end{cases} \quad \text{and } k \in [0,\ 1] \tag{8}$$

The current sharing error k is valid when the current sharing error k is between 0 and 1. If the current sharing error k=0 or k=1, then one of the phases is providing all the power, and the other phase is not providing any power. The conditions of the current sharing error k<0 or k>1 does not exist because this would one of the phases absorbing power. The load current sharing error σ_{load} is defined by

$$\sigma_{load} = \text{abs}\left(\frac{I_{01}-I_{02}}{I_{01}+I_{02}}\right) = \text{abs}(1-2k),\ k \in [0,\ 1] \tag{9}$$

where abs(x) is the absolute value function.

The resonant current sharing error $\sigma_{Resonant}$ is defined by:

$$\sigma_{Resonant} = \frac{|\text{rms}(i_{Lr1}) - \text{rms}(i_{Lr2})|}{|\text{rms}(i_{Lr1}) + \text{rms}(i_{Lr2})|} \tag{10}$$

where rms means root mean square.

Table 1 shows parameters of the two-phase LLC converter used in the current sharing analysis. The full load power of each phase is 12 V @25 A. Two load conditions are considered: full load (12 V @50 A) and half load (12 V @25 A).

TABLE 1

(Nominal parameters)

Resonant inductor Lr	29 μH
Resonant capacitor Cr	12 nF
Magnetic inductor Lm	95 μH
Transformer ratio n	20
Resonant frequency fr	270 KHz
Output voltage Vo	12 V (rated voltage)
Total Output load Ro	0.24 Ω (full power 600 W) 0.48 Ω (half power 300 W)

FIGS. **3-6** show load current sharing error σ_{load} of the known two-phase LLC resonant converter without current sharing shown in FIG. **30** with 2%, 5%, and 10% differences in component tolerances. If (a, b, c)=(1, 1, 1), then the first and second phases have the same parameters, which results in the load current be perfectly shared and σ_{load}=0. If (a, b, c)=(1.05, 1.05, 1.05), then the resonant component parameters in phase 2 are 5% more than the resonant component values in phase **1**. FIG. **3** shows the load current and the load current sharing error with 2% difference in component tolerances. Only the second phase converter provides load power when the total load current is changed from 5 A to 45 A, the load current sharing error is 100%. FIGS. **4** and **5** show similar results when the component tolerances differences are 5% and 10%. Thus, a two-phase LLC resonant converter without current sharing cannot adequately share the load current. The rated current is 25 A for each phase, which means that the two-phase converter cannot provide the total 50 A power.

FIGS. **6-8** show load current sharing error σ_{load} of a two-phase LLC resonant converter using the common-inductor current-sharing method shown in FIG. **1** with 2%, 5%, and 10% differences in component tolerances. FIG. **6** shows the load current and the load current sharing error with 2% difference in component tolerances. The maximum load current sharing error is 0.95%. The phases share almost the same load current. FIGS. **7** and **8** show similar results when the component tolerances differences are 5% and 10%. The maximum load current sharing error is 2.3% and 4.5%, respectively. The phases share almost the same load current.

A 600 W, two-phase LLC resonant converter prototype was built using the common-inductor current-sharing method to verify the feasibility and to demonstrate the advantages of the common-inductor current-sharing method. The circuit diagram of the prototype is shown in FIG. **1**. The parameters of the prototype are shown in Table 2.

TABLE 2

(Prototype parameters)

Switching frequency	180 kHz-270 kHz
Input Voltage Vin	340 V-400 V
Output Voltage Vo	12 V
Output Power	300 W × 2
Transformer Ratio n	20:1
Output Capacitance Co	1790 μF
Series Capacitance Cr	12 nF + 5%
Resonant Inductance Lr	22.5 μH (Phase 1) 24.5 μH (Phase 2)
Leakage Inductance Le	6 μH (Phase 1) 6.5 μH (Phase 2)
Magnetizing Inductance (Lm)	95 μH (Phase 1) 92 μH (Phase 2)

FIGS. **9** and **10** show simulated waveforms at 15 A and 25 A load currents of the known two-phase LLC resonant converter without current sharing in FIG. **30**. The rated current for each phase is 25 A, which means that the two-phase converter does not provide the total 50 A load current. When the total load current is larger than 25 A, the second phase load current will exceed the rated current as shown in FIG. **10**. To escape the overcurrent of each phase in which the phase current exceeds the rated phase current, the total maximum 25 A current experiment is done without current sharing. Because the output voltage has a switching frequency ripple, the load current lo**1** has a high frequency ripple to charge or discharge the output capacitor C_{o2}. Thus, the converter has negative high frequency current or positive high frequency current. The average load current is zero. Thus, only phase **1** provides the load power.

FIGS. **11-13** show simulated waveforms at 15 A, 25 A, and 50 A load currents of the two-phase LLC resonant converter using the common-inductor current-sharing method shown in FIG. **1**. The load current difference is reduced from 15 A to 3 A between FIG. **9** and FIG. **11**. The load current difference is reduced from 25 A to 0.5 A between FIG. **10** and FIG. **13**. FIG. **13** shows the good load sharing for a 50 A load current.

The resonant currents i_{Lr1}, i_{Lr2} and the rectifier currents i_{rect1}, i_{rect2} are almost the same for the two phases. Thus, the load current is shared by the two phases. Good resonant inductor current sharing guarantees good load current sharing as indicated in FIGS. **9-13**.

FIGS. **14** and **15** show simulated waveforms at steady-state 180 W and 300 W loads of the known two-phase LLC resonant converter without current sharing in FIG. **30**. FIGS. **14** and **15** show the simulated waveforms of the output voltage Vo and the resonant current i_{Lr1}, i_{Lr2}. The resonant current i_{Lr1} is almost a triangle waveform, which means phase **1** provides very little of the power of the output load. FIGS. **16-18** show simulated waveforms at steady-state 180 W, 300 W, and 600 W loads of the two-phase LLC resonant converter using the common-inductor current-sharing method shown in FIG. **1**. The resonant currents i_{Lr1}, i_{Lr2} are almost identical. There is a very small angle difference between the resonant currents i_{Lr1}, i_{L2} at the different loads.

FIG. **19** shows the resonant currents of the known two-phase LLC resonant converter without current sharing in FIG. **30**, FIG. **20** shows the resonant currents of the two-phase LLC resonant converter using the common-inductor current-sharing method shown in FIG. **1**, and FIG. **32** shows the resonant currents of the two-phase LLC resonant converter using the common-inductor current-sharing method discussed below.

The relative resonant current increases from 10% to 28% as load current increases from 5 A to 25 A in FIG. **19**. The relative resonant current decreases from 2.3% to 0.44% as load current changes from 5 A to 50 A in FIG. **20**. Thus, the resonant current is significantly reduced using the common-inductor current-sharing method.

FIG. **21** shows a modular DC/DC converter with m phases connected in parallel. The modular DC/DC converter uses the common-inductor current-sharing method. The modular DC/DC converter includes a DC input that is connected to each of the m phases. For phase k, where k=1 to m, the converter includes two power switches Qk**1**, Qk**2** connected to the DC input; transformer Tk connected to magnetizing inductor Lmk, resonant inductor Lrk, and resonant capacitor Crk; and two synchronous rectifiers SRk**1**, SRk**2** that provide a rectified output to the output capacitor C_{ok}. It is possible to use passive diodes instead of active synchronous rectifiers to provide a rectified output. The m phases are connected in parallel to provide an output voltage V_o. The load is represented by resistance R_L.

Each of the m phases includes an inductor L_s that is connected between the power switch Qk**2** and the transformer Tk. The inductors L_s are connected in parallel and are implemented as a single inductor. Each of the inductors L_s includes a left node and a right node. All of the left nodes of the inductors L_s are connected to the ground of DC input, and all of the right nodes of the inductors L_s are connected together. Because the inductors L_s are connected together, they define an equivalent inductance with a common branch through which the current of the phases flow. A sharing line is connected to the right node between the inductor L_s and the transformer Tk in each phase. The inductors L_s of each phase are connected in parallel with each other. The inductors L_s are charged and discharged by the resonant current in each phase because they are connected by the common branch. When the resonant currents are different between the phases, the inductors L_s build up a connection of each phase through the voltages of the inductors L_s, eliminating the circulated current and sharing the load.

FIG. **22** is similar to FIG. **21** expect that the m phases share the capacitor C_s instead of inductor L_S. The converter in FIG. **22** uses a common-capacitor current-sharing method according to a comparative example. The capacitors C_s of each phase are connected in parallel with each other. The capacitors C_s are charged and discharged by the resonant current in each phase because they are connected by the common branch. When the resonant currents are different between the phases, the capacitors C_s builds up the connection of each phase through the voltage of capacitors C_s, eliminating the circulated current and sharing the load. In FIG. **22**, only an additional resonant capacitor Crk is used. The value of the resonant capacitor Crk can be small compared to the value of the known series DC capacitor discussed above. In addition, in FIG. **22**, the value of the total resonant capacitor can be divided into two parts: (a) two capacitors connected in series and (b) one capacitor connected in parallel. Thus, only a portion of the resonant capacitor Crk is connected in parallel as a common capacitor. In FIG. **22**, if the right node of capacitors C_s are not connected, then the total capacitance of each phase is the capacitance of the capacitor C_s plus the capacitance of the resonant capacitor Crk. Thus, the capacitance can be divided into two parts. If the right nodes of the capacitors Cs are connected together, then all capacitors Cs are connected in parallel because of their left nodes are also connected together. FIGS. **20** and **32** show that the common-inductor current-sharing method can achieve a resonant current error of only 0.44% at 600 W total load power, while the common-capacitor current-sharing method is only able to achieve a resonant current error of 5% at 600 W total load power.

In FIGS. **21** and **22**, all of the inductance or capacitance is connected in parallel, which means one inductor L_s or one capacitor C_s can be used. It is also possible to divide the inductance or the capacitance so that two inductors or two capacitors are used. The best performance can be achieved when all of inductance or capacitance are connected in parallel. Each of the inductors L_s preferably have the same value, and each of the capacitors C_s preferably have the same value. However, because of the component tolerances in the different phases, the inductors L_s and the capacitors C_s can have different values.

FIG. **23** is a specific example of FIG. **21** in which the shared inductor L_s is the resonant inductor Lrk, and FIG. **24** is a specific example of FIG. **22** in which the shared capacitor C_s is the resonant capacitor Crk. The total inductor value is the same in FIGS. **21** and **23**, and the total capacitor value is the same in FIGS. **22** and **24**. In FIG. **21**, a portion of the value of the resonant inductor Lrk is included in the common branch to share the phases, and in FIG. **23**, the total value of the resonant inductor Lrk is included in the common branch to share the phases. In FIG. **22**, a portion of the value of the resonant capacitor Crk is included in the common branch to share the phases, and in FIG. **24**, the total value of the resonant capacitor Crk is included in the common branch to share the phases.

FIG. **25** shows two three-phase modules connected in parallel and using the common-inductor current-sharing method. Each module has three phases, and the resonant inductor L_s is shared between the modules with phase shift modulation. The two modules are connected by the shared inductor L_s. The two inductors L_s are connected in parallel and are implemented as one combined inductor. Two inductors L_s are combined and shared between the two converters.

FIG. **26** is similar to FIG. **25** except that capacitor C_s is shared instead of inductor L_s. The two three-phase modules in FIG. **26** use the common-capacitor current-sharing method. In FIG. **26**, the resonant capacitor C_s is shared between the modules with phase shift modulation. The two modules are connected by the shared capacitor C_s. The capacitors C_s are connected parallel with each other. The capacitor C_s is included in the common branch, which can influence the distribution of the resonant current through the voltage of the common capacitor C_s.

It should be understood that the foregoing description is only illustrative of the present invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the present invention. Accordingly, the present invention is intended to embrace all such alternatives, modifications, and variances that fall within the scope of the appended claims.

What is claimed is:

1. An LLC resonant converter comprising:

a voltage input;

a voltage output;

a first phase including:

  a first transformer with first primary and first secondary windings;

  a first primary circuit connected to the voltage input and the first primary winding, the first primary circuit including:

    a first resonant capacitor;

    a first magnetizing inductor connected in parallel across the first primary winding; and

    a first resonant inductor; wherein

    the first resonant capacitor, the first magnetizing inductor, and the first resonant inductor are connected in series;

  a first secondary circuit connected to the first secondary winding and the voltage output, the first secondary circuit including a first rectifying circuit; and

  a second phase including:

  a second transformer with second primary and second secondary windings;

  a second primary circuit connected to the voltage input and the second primary winding, the second primary circuit including:

    a second resonant capacitor;

    a second magnetizing inductor connected in parallel across the second primary winding; and

    a second resonant inductor; wherein

    the second resonant capacitor, the second magnetizing inductor, and the second resonant inductor are connected in series;

  a second secondary circuit connected to the second secondary winding and the voltage output, the second secondary circuit including a second rectifying circuit; wherein

the first primary circuit includes a first shared inductor with first and second ends;

the second primary circuit includes a second shared inductor with first and second ends;

the first and second shared inductors are connected in parallel with each other such that the first ends of the first and second shared inductors are directly connected to each other, and the second ends of the first and second shared inductors are directly connected to each other; and

the first and second primary circuits do not include a capacitor that is connected in parallel with each other.

2. The LLC resonant converter of claim **1**, wherein the first and second rectifying circuits include synchronous rectifiers.

3. The LLC resonant converter of claim **1**, wherein the first phase includes a first output capacitor, and the second phase includes a second output capacitor.

4. The LLC resonant converter of claim **1**, further comprising at least one additional phase including at least one additional shared inductor; wherein

the at least one additional shared inductor is connected in parallel with the first and second shared inductors.

5. The LLC resonant converter of claim **1**, wherein:

the first shared inductor is the first resonant inductor; and

the second shared inductor is the second resonant inductor.

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