A New Efficient Rectifier Circuit Based on Nonlinear Inductance Impedance Conversion

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Abstract. The conventional capacitor filter bridge rectifier circuit has the characteristics which the input current is discontinuous, peaked and contains high-order harmonics. A new nonlinear inductance impedance transformation circuit is presented based on the characteristics of general rectifier circuit in this paper. Before being used in capacitance filter of the general bridge rectifier and it ensures that when the power voltage is lower than that of rectifier the value of nonlinear resistance will vary with the voltage to check the dead area range for input current and decrease harmonics. It improves the character of power factor, and is important to energy saving.

Keywords: Rectifier circuit; Inductance; Nonlinear; Resistance conversion.

1. Introduction
In today's life and industrial production, a lot of dc power supplys are still used in supply many places[1]. As a kind of conventional energy conversion circuit, which obtains energy from AC mains power or standby power supply and converts it into DC energy to charge the battery and supply power to communication equipment, the capacitor filter bridge rectifier circuit has the characteristics of simple circuit composition, high efficiency and low cost. It is widely used in communication field, microcomputer system, power electronic device and various electrical equipment[2]. However, the input current is discontinuous, peaked and contains high-order harmonics[3]. Especially with the increase of application field and quantity, it will cause harmonic pollution, current waveform distortion, line loss increase and so on[4].

In this paper, an inductive non-linear impedance conversion link which changes with the voltage is proposed and integrated into the capacitor filter of the conventional bridge rectifier circuit based on the analysis of the input current variation of the conventional single-phase rectifier circuit. The nonlinear impedance value will also change accordingly. The current can be continued to effectively overcome and narrow the dead time range of the input current, thus reducing the harmonic content of the input current and improving the power factor quality of the system.

2. Input Characteristics of Single Phase Bridge Rectifier with Conventional Capacitor Filter
The uncontrollable bridge rectifier circuit with capacitor filter and the input characteristic waveform are shown in Fig. 1[5].

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During the period from zero crossing of \( u_2 \) positive half cycle to \( \omega t = 0 \), due to \( u_2 < u_d \), all diodes are not conductive, and capacitor C discharges to R to provide the current required by the load. Meanwhile \( u_d \) decreases exponentially. When \( u_2 > u_d \), \( VD_1 \) and \( VD_4 \) are turned on. If the tube voltage drop is ignored, the AC power supplies the capacitor and the load R until \( u_2 = u_d \).

In the negative half cycle of \( u_2 \), switch to \( VD_2 \) and \( VD_3 \), and repeat the above working process. If \( u_2 = \sqrt{2}U_2 \sin(\omega t + \delta) \), the output current of the transformer is:

\[
i = i_d = i_c + i_R = C \frac{du_2}{dt} + \frac{u_2}{R} = \sqrt{2} \omega C U_2 \cos(\omega t + \delta) + \frac{\sqrt{2} U_2}{R} \sin(\omega t + \delta)
\]

Let the conduction angles of \( VD_1 \) and \( VD_4 \) or \( VD_2 \) and \( VD_3 \) are \( \theta \), and substitute the boundary value condition \( i_d(\theta) = 0 \) into the above equation\(^6\):

\[
\theta + \delta = \pi - \arctan(\omega RC)
\]

Obviously, the angle \( \delta \) of the zero crossing point of \( u_2 \) and the conduction angle \( \theta \) of the input current in the half cycle are all related to \( \omega RC \). Especially from formula (2-2), because of \( \theta < \pi \), in this kind of rectifier circuit, although the input voltage is sine wave, the input current \( i_2 \) can only conduct in the range of \( |u_2| > u_d \) in one cycle, so it will be an intermittent current with dead zone and peaked wave shape.

The input voltage and current curve of conventional circuit is shown in Fig. 2.

3. Inductive Nonlinear Impedance Conversion Circuit

The inductance type nonlinear impedance conversion circuit composed of two inductors and diodes is shown in Fig. 3.
Figure 3. Inductive nonlinear impedance conversion circuit.

For the sake of illustration, it is assumed that the positive direction of current and voltage is shown in the diagram. Because the current can only flow in one direction, only two cases of positive and negative voltage are considered to explain the impedance transformation process.

When the applied voltage is positive, $D_2$ is cut off because of the appearance and polarity of the back EMF. From the input, the two inductors are connected in parallel. The equivalent inductance is $L_1 L_2 / (L_1 + L_2)$, and the inductance current is $i_1 = i_2 = i / 2$.

When the applied voltage is negative, such as $L_1 \neq L_2$, at the beginning of the transition process, the current of $i_1 - i_2$ in the small inductance $L_1$ will continue with $D_3$ due to the different current sizes of the two inductors. At this time, the current value in inductance $L_2$ is $i_2$, and the equivalent inductance is $L_1$. After the transition process, $D_3$ is cut off and the two inductors are connected in series. The equivalent inductance is $L_1 + L_2$ and the current is $i_1 = i_2 = i$. The parameter relationship of the whole process is shown in Table 1.

| Table 1 Relationship between parameters (if $L_1 < L_2$). |
|----------------------------------------------------------|
| The voltage U is positive | The voltage U is negative |
| State of D1 | Turn on | Cut off | Cut off |
| State of D2 | Cut off | Turn on | Turn on |
| State of D3 | Turn on | Turn on | Cut off |
| The relationship between i1 and i2 | $i_1 > i_2$ | $i_1 > i_2$ | $i_1 = i_2$ |
| $i = i_1 + i_2$ | $i = i_1$ | $i = i_1 = i_2$ |
| Connection mode of L1 and L2 | Parallel | L2 and D3 connected in series with L1 | Series |
| $L$ | $L_1 L_2 / (L_1 + L_2)$ | $L_1$ | $L_1 + L_2$ |

In this way, the equivalent inductance is changed into $L_1 L_2 / (L_1 + L_2)$ and $L_1 + L_2$ depending on the direction of voltage, so the purpose of nonlinear impedance transformation can be realized [7].

4. A New Type of Inductive Nonlinear Impedance Conversion Rectifier Circuit

4.1. Circuit Composition

In this paper, the inductive nonlinear impedance transformation is applied to the bridge rectifier circuit to improve the capacitor filter. The new inductive nonlinear impedance transformation rectifier circuit is shown in Fig. 4.
Figure 4. A new type of impedance conversion rectifier circuit.
In order to explain the working process conveniently, suppose the inductance $L_1 = L_2$. In the figure, in order to ensure that $U_d$ remains unchanged, and to change the amplitude of DC voltage $U_c$ directly output by the rectifier bridge through the transformation of nonlinear impedance, so as to continue the range of $|u_s| > u_c$, to widen the conduction angle $\theta$ of input current, a small capacity capacitor $C$ is specially set.

4.2 Working Mode Analysis
The working mode analysis of the new inductive nonlinear impedance conversion rectifier circuit is shown in Fig. 5.

Figure 5. Analysis of the working mode of a novel inductive nonlinear impedance conversion rectifier circuit.
When the power supply voltage $u_s$ is positive half cycle and $u_s < u_c < u_d$, the working mode is the same as that of the conventional rectifier circuit, and the equivalent impedance link does not work. The filter capacitor supplies power to the load, as shown in Figure 5 (a).

With the increase of capacitor $C$ charging voltage $u_c$, when $u_c > u_d$, diode $D_2$ is in the cut-off state, and the two inductors of nonlinear impedance transformation link are connected in parallel. When the power supply charges capacitor $C$, current flows into filter capacitor $C_d$ through transformation link to charge capacitor $C_d$. Refer to Fig. 5 (b) state.

When \( u_c < u_d \), diode \( D_2 \) is turned on (ignoring tube voltage drop) due to the change of inductance back EMF polarity. The two inductors of nonlinear impedance transformation link are connected in series to ensure the current flowing from capacitor \( C \) to filter capacitor \( C_d \) through the transformation link, and the filter capacitor voltage \( u_d \) can continue to rise. See Figure 5 (c) state.

At the same time, due to the change of impedance and the superposition of back EMF, the voltage \( u_c \) of capacitor \( C \) decreases, the rate of change and the amplitude of decrease increase. No matter whether \( u_c \) is greater than \( u_d \) or not, the difference between \( u_c \) and supply voltage \( u_s \) is further increased, so that the duration of power supply current and conduction angle are widened.

When the amplitude of \( u_s \) decreases further until \( u_s < u_c \), the AC side will no longer flow into the DC side, and only the filter capacitor \( C \) will discharge to reduce the DC voltage to meet the load. It is as shown in Fig. 5 (d) [8].

Based on the above analysis, by adding a nonlinear impedance transformation link and automatically changing the connection form of nonlinear impedance according to the changes of \( u_c \) and \( u_d \) voltage, Fig. 5(a) and Fig. 5(c) are added to the conventional rectifier circuit. In the condition that the DC voltage \( U_d \) required by the load is kept constant, the circulation period of the input current is widened, the dead time of the current \( i_s \) effectively eliminated and shortened, and the generation of high-order harmonics is suppressed.

5. Experimental Results
A new inductive nonlinear impedance conversion rectifier circuit is composed of \( V_s = 220\sqrt{2} \sin 314t \), \( L_1 = L_2 = 3.4mH \), \( C = 390\mu F \), \( C_d = 1800\mu F \), \( I_d = 10A \). The system experiment and computer simulation are carried out. The results are shown in Fig. 6 and Fig. 7.

![Figure 6. Simulation curve of input voltage and current.](image)

![Figure 7. Experimental curve of input voltage and current.](image)

It can be seen from the figure that the input current waveform has been fully improved, and the range of current dead zone can be further shortened by properly selecting parameters.

6. Conclusion
This paper presents and analyzes the composition and principle of inductance type nonlinear impedance transformation, and directly applies it to the conventional capacitor filter rectifier circuit.
Combined with the working process of the circuit, the realization mechanism of shortening the dead time of input current and widening the conduction angle is analyzed. The feasibility of this method to improve the performance and quality of the rectifier circuit is verified by experiments. It can be seen from the figure that the input current waveform has been fully improved, and the range of current dead zone can be further shortened by properly selecting parameters. The application of the circuit to the power conversion device, office and household appliances, steel and non-metallic industries, can greatly reduce the harmonic content of the system, improve the power factor quality of the system, and achieve the purpose of energy saving. For mechanical devices, it can also avoid abnormal sound, overheating, impact, vibration, burning loss and other phenomena caused by high-order harmonic current, as well as possible misoperation and control. These are also of great significance for improving the working quality of related systems, increasing efficiency and energy saving.

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