COMPENSATED SINGLE-PHASE RECTIFIER

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Abstract. Paper describes methods of rectified DC pulsation reduction adding a compensation node to a single phase rectifier. Device is related to converters of electrical energy and it can be used in power electronics. Purpose of single phase compensated rectifier is to reduce load voltage pulsations. Several methods of compensation are observed, load characteristics are compared to a simple rectifier. Load voltage is compensated using compensation switch. It is operated so that rectifier output voltage pulsation is minimal. This current pulsation reduction effect is achieved so that the elevated voltage node is operating as an additional power source for load. Operation of compensation switch is controlled by comparing of two voltages, comparing reference voltage with voltage on load. While these voltages are equal or load voltage is greater than reference voltage, load voltage is not compensated. As soon as load voltage less than reference voltage, the compensation current is increased in proportion of difference of compared voltages. Load voltage compensation process goes on continuous.

Keywords: DC, compensation, capacitor, pulsation, load characteristic, reference voltage.

Introduction

In many cases there is a need to rectify single-phase AC. In addition, for example, in some technical applications (single-phase AC electrified transport and other) power has many hundreds of kilowatts. High quality rectified voltage of most of the rectifier circuits has a rectifier bridge circuit, but also in the rectified voltage there is a high variable voltage component that does not provide high-quality load voltage. For the voltage shape improvement there is the capacitive filter widely used [1,3], which is charging at the moment when AC voltage reaches its peak and discharges when the output voltage decreases shifting the stored energy to the load thus equalizing the load voltage. While the rectifier with the capacitance filter improves the rectified voltage form, it has the disadvantage that its AC current has a very bad shape with large magnitude because charging takes place in a very short time interval.

When connecting the capacitor in parallel to the bridge rectifier output, the load voltage shape significantly improves. However, the capacitor capacity is large, especially if the load current is large. The filter capacity can be approximately defined as

$$C = \frac{I_{load}(0.25T + \frac{1}{\omega}\arcsin(1-\Delta U^*))}{\Delta U}, \tag{1}$$

where ΔU is voltage reduction of the amplitude value, U_m half period $0.5T=0.5/f$ while, but $\omega=2\pi f$ (ΔU^* is ΔU and U_m ratio).

If, for example, the load current is 100 A, ΔU=20 V, U_m=312 V, f=50 Hz, then the necessary capacity of the capacitor is 44250 µF. Such a capacitor, while half-period is charging in a very short time with a current amplitude of more than 1.5 kA and the current THD = 1.66, i.e., results in a very bad shape of the current.

The form of network current can be significantly improved involving an inductance into the AC power side [2]. This inductance can be approximately calculated as

$$L = \frac{0.63 \cdot \Delta U \cdot 2(0.25T - \frac{1}{\omega}\arcsin(1-\Delta U^*))}{1.7 I_{load}}, \tag{2}$$

and in case of this example, its inductance must be 29 mH having a RMS current of about 120 A and saturation current near 200 A. Although such coils and filter capacitor dimensions and weights are large, this significantly degrades the efficiency of the system.

These deficiencies can be prevented adding to a simple rectifier an elevated voltage compensation junction, circuits can be created in a number of ways, some of which are observed in this study, and the solution is called the single-phase compensated rectifier. This rectifier output curve compared to the rectifier, which has only the capacitive filter, is less dropping within incident of load current rise and within a certain range of load current growth, the load voltage remains constant.

Development of single-phase compensated rectifier

The compensated rectifier is developed providing of an additional direct voltage source, a voltage just above the $U_m(1–\Delta U^*)$ value, and connecting it to the load through the transistor VT that is operating in emitter follower mode with the emitter base steering voltage $U_m(1–\Delta U^*)$ (Fig. 1). When the load voltage instantaneous value is slightly below the $U_m(1–\Delta U^*)$, the transistor opens and the compensation voltage will be connected to the load by maintaining the load voltage instantaneous value at the reference voltage $U_m(1–\Delta U^*)$ level. Using the compensated rectifier, part of the load power is provided from the unregulated bridge rectifier and part from the compensation unit.

The operation time of each of the sources is depending on the level of ΔU^*: if it is higher, the source of compensation operates longer:

$$t_{comp} = \frac{2}{\omega}\arcsin(1-\Delta U^*)\,, \tag{3}$$

but the operation time of the main rectifier is t_{pT}=0.5T–t_{comp}. Curves of $t^*_{comp}=t_{comp}2f=f(\Delta U^*)$ and $t^*_{pT}=f(\Delta U^*)$ at frequency f=50 Hz are shown in Fig. 2. a. As it can be seen both operation times are equal at ΔU^*=0.29.

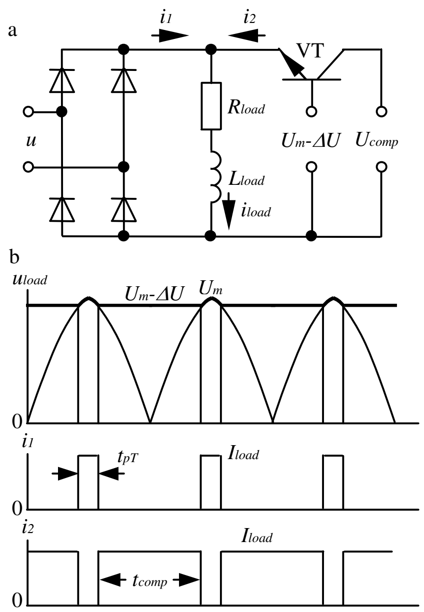

Fig. 1. **Compensated rectifier circuit (a) and diagrams (b)**

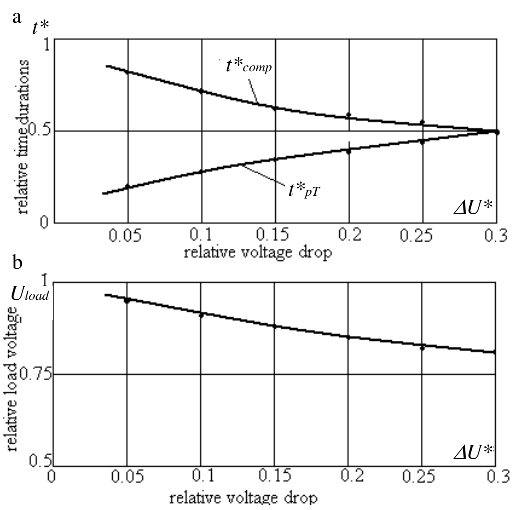

Fig. 2. **Dependence of conductivity times of both part of rectifier (a) and averaged voltage of load (b) on relative voltage drop**

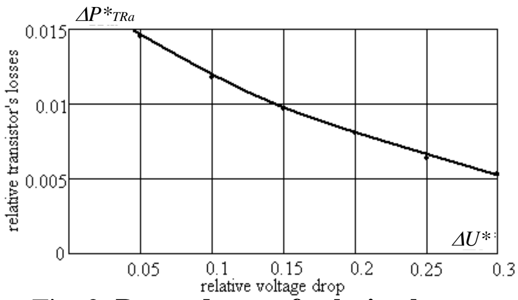

Fig. 3. **Dependence of relative losses of transistor on relative voltage drop**

Load voltage average value can be determined as

$$U^*_{load} = \frac{U_{load}}{U_m} = 1-\Delta U^* + 0.63.\Delta U^* \cdot t^*_{pT}\,. \tag{4}$$

This curve, depending on the ΔU^* at f = 50 Hz is depicted in Fig. 2. b. As it can be seen as ΔU^* goes higher, U_{load}^* goes lesser and at ΔU^*= 0.3 it is 0.7956. At the same time it should be noted that the main rectifier bridge rectified DC voltage ratio to U_m is 0.6338, i.e., lesser than in the compensation system at ΔU^* = 0.3.

The transistor VT of the compensation circuit operates in the emitter follower mode, i.e., it has large power losses. When the transistor is conducting, the collector-emitter voltage is $U_{VT} = U_{comp} - U_m + \Delta U$, where U_{comp} is a compensation source DC voltage, which must be greater than $U_m(1-\Delta U^*)$, i.e., the reference voltage. Current, conducted by the transistor is I_{comp}. So the average transistor dissipated power is

$$\Delta P_{TRa} = I_{comp} \cdot (U_{comp} - U_m + \Delta U) \cdot t^*_{comp} = \frac{(U_m - \Delta U + 0.63 \cdot \Delta U \cdot t^*_{pT})}{R_{sl}} \cdot (U_{comp} - U_m + \Delta U) \cdot t^*_{comp} \cdot \quad (5)$$

In order to reduce power losses, it is rationally to adopt U_{comp} only slightly (by 2-5 V) greater than the reference voltage $U_m(1-\Delta U^*)$. Introducing the base capacity U_m^2/R_{load}, the transistor relative loss expression will be

$$\Delta P^*_{TRa} = (1 - \Delta U^* + 0.63 \cdot \Delta U^* \cdot t^*_{pT})(U^*_{comp} - 1 + \Delta U^*) \cdot t^*_{comp}, \quad (6)$$

where it would be appropriate to accept U_{comp}^*=1.02(1-ΔU^*). Basing on this assumption, at f=50 Hz calculated curve ΔP_{Tra}^*=f(ΔU^*), displayed in Figure 3. As it can be seen, at ΔU^* increase the relative loss decreases. At ΔU^*=0.3 the relative loss is 0.0055, or at U_m=312V, R_{load}=2 Ω, it will be 268 W. Noticing that the power transistor must be rated for at least about 150A and the loading capacity will be almost 31 kW, the dissipated power will be small.

The main rectifier must be calculated on the average load current

$$I_{1average} = \frac{U_m - \Delta U + 0.63 \cdot \Delta U \cdot t^*_{pT}}{R_{sl}} \quad (7)$$

or

$$I^*_{1average} = \frac{I_{1average} \cdot R_{sl}}{U_m} = 1 - \Delta U^* + 0.63 \cdot \Delta U^* \cdot t^*_{pT} \cdot$$

While the compensation source average current

$$I^*_{2average} = (1 - \Delta U^* + 0.63 \cdot \Delta U^* \cdot t^*_{pT}) \cdot t^*_{comp}, \quad (8)$$

but this source power will be

$$P^*_{comp} = \frac{P_{comp} \cdot R_{load}}{U_m^2} = I^*_{2average} .1.02 \cdot (1 - \Delta U^*) \cdot \quad (9)$$

This way, at ΔU^*=0.3, the compensation source should be calculated on 0.281 unit of the relative power, or, for example, at U_m=312V, R_{load}=2 Ω compensation power capacity must be 13.7 kW.

Development of compensation source

Such source can be created as a bridge rectifier with the connected capacitor-reactor filter at its output; the compensation source will be able to feed from the same AC as the main rectifier (Fig. 4). The required coil inductance and capacitor capacitance have to provide that instantaneous meanings of the capacitor C_F voltage will be more as U_m(1-ΔU^*). Calculation of such filter approximately [2] can be realized at approach that the values of the capacitor voltage are decreasing linearly in the way of consuming from the junction compensation current (Fig. 5).

$$u_{cF} = U_{c\min} + \Delta U_{cF} - \frac{I_{load} \cdot t}{C}, \quad (10)$$

where U_{cmin} is the minimal value of voltage, ΔU_{cF} is the voltage difference between the maximum and minimum values, but the time t is between 0 un t_{comp}. In a similar way the capacitor voltage is rising in the way of operation of the main rectifier:

$$u_c = U_{c\min} + \frac{I_{ca}.t}{C}, \tag{11}$$

where I_{ca} is an averaged value of the capacitor current in the way of operation of the main rectifier when t is between 0 to t_{pT}.

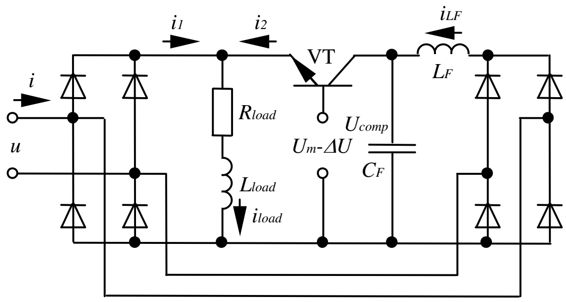

Fig. 4. **Possible scheme of realization of compensation source**

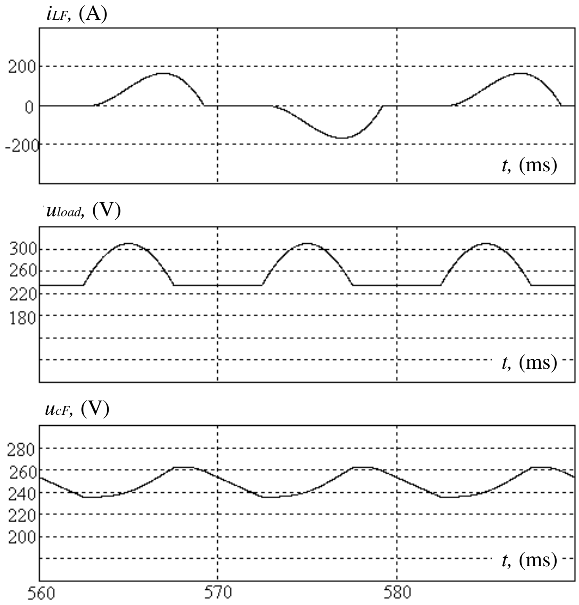

Fig. 5. **Voltage and current diagrams of filter on Fig. 4**

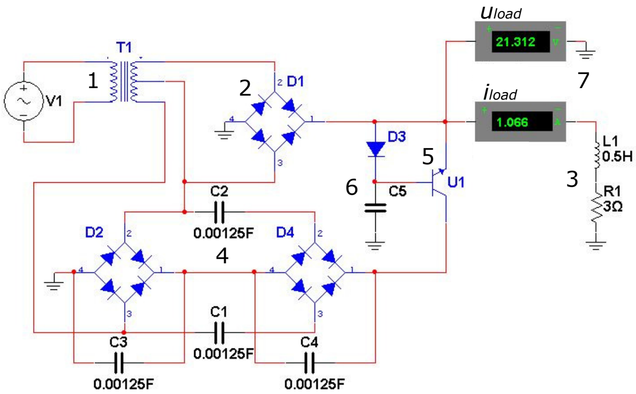

Fig. 6. **Compensated single-phase rectifier with voltage doubler**

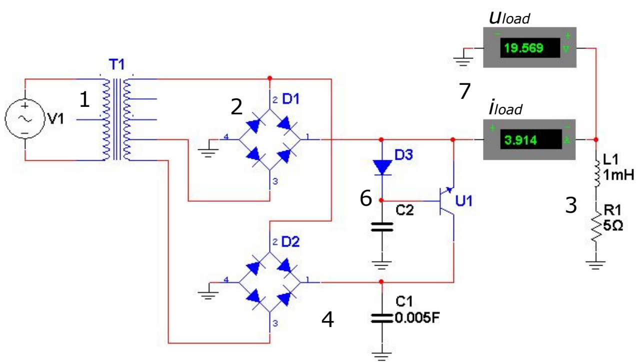

Fig. 7. **Compensated single-phase rectifier with the additional elevated voltage rectifier and capacitance**

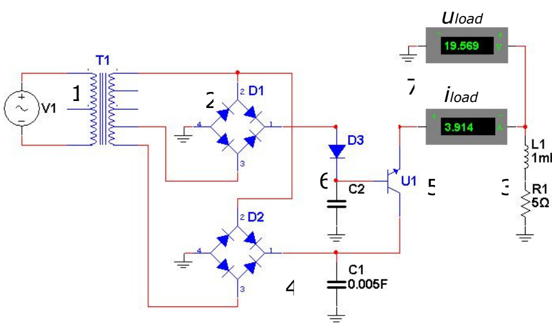

Fig. 8. **Compensation rectifier with the additional elevated voltage node**

Accepting necessary ΔU_{cF}, from (10) the capacitance can be found:

$$C = \frac{I_{load} .t_{comp}}{\Delta U_{cF}}, \tag{12}$$

but from (11) - the necessary averaged current of capacitor charging is obtained

$$I_{ca} = \frac{\Delta U_{cF} .C}{t_{pT}}. \tag{13}$$

As it can be seen from Fig. 5 this current is slightly smaller as magnitude of the reactor current I_{Lm} which is about 1.3 times bigger. Inductance of the coil can be found from a simplified equation for the capacitor charging circuit

$$L_F \frac{I_{Lm}}{t_{pT}} = 0.63(U_m - U_{c\,\min}) - 0.5\Delta U_{cF} \cdot$$

Here from

$$L_F = \frac{[0.63(U_m - U_{c\min}) - 0.5\Delta U_{cF}] \cdot t_{pT}^2}{1.3 I_{sl} \cdot t_{comp}}. \tag{13}$$

It is assumed that current through the reactor is passing 1.2 times longer than main rectifier operation interval, RMS value of the reactor current can be found as:

$$I_{Lef} = I_{ca}\sqrt{2.4 t_{pT} \cdot f}\ . \tag{14}$$

If, for instance, ΔU^*=0.3, R_{load}=2 Ω, I_{load}=125 A, f=50 Hz, U_{cmin}=230V, ΔU_{cF}=35 V, then L=1.05 mH, C=17100 μF, but RMS current of the reactor is about 90 A. If the compensation scheme is not used in the case of the rectifier with the filter must be L=1.45 mH with RMS current 140 A. As the mass of the reactor is proportional to LI_{ef}^2 it should be possible to state that the reactor of the filter for the compensated scheme will be three times lighter. But the capacitance of the filter capacitor for the compensated scheme has to be C=17100 μF when in case of ordinary rectifier only 9656 μF. Rising of the capacity is need because providing condition $U_{cmin}> U_m(1-\Delta U^*)$.

It is possible to apply another scheme with the capacitor type voltage doubler (Fig. 6). With the numbers the following elements are indicated: 1 – transformer secondary winding with a centre tap; 2 – main rectifier bridge; 3 – active inductive load; 4 – diode-capacitor voltage doubler; 5 – compensation transistor; 6 – reference voltage unit, which is presented as diode and capacitor; 7 – *Mltisim* virtual instruments to collect data for load characteristics of the system.

In Fig. 7 another version of the compensation voltage source is presented when it is possible to apply a transformer with elevated value of voltage of the secondary part of the winding. In addition, in this case, the transformer secondary winding has the mid-point output, but the compensation rectifier is connected to the transformer output voltage of about 40% higher than the output at which it is connected to the main rectifier. The action differs only in that the load is compensated by the lower voltage level and simpler compensation accumulator than in the case with the voltage doubler. The single-phase compensation rectifier shown in Fig. 8 is similar to the rectifier in the previous case, but the difference is that the power rectifier with the capacitor 6 performs only the reference voltage function. The outer curve of this circuit is shown as 3rd in Fig. 7 and 8.

Investigation of load characteristics

For the above mentioned schemes simulation programs have been used to obtain their load characteristics, i.e. dependence of the load voltage on load current. This was done using computer programs *PSIM* and *MultiSIM*. The characteristics are presented in Fig. 9 and 10. The load characteristics of the system with the voltage doubler are shown as 2nd in Fig 7 and 8. The characteristics for the circuit with additional elevated voltage are shown as 1st in Fig. 9 and 10. The load characteristics for the scheme 8 are presented as 3rd. The characteristics 4 are for the ordinary rectifier with the capacitor at output.

The comparison of the efficiency of the rectifier compensation option to the simple rectifier with the capacitance filter load characteristics of four rectifier circuits is shown in Fig. 9 and 10. The characteristics are taken by changing the rectifier load gradually from 0 to large values and collecting data of average current and voltage measurements. All observed circuits had been measured at each load value but the load current and voltage average value reading is performed and the data are summarized in Fig. 9 and 10.

The compensated rectifier circuits were simulated according to the pictures illustrated in Fig. 6, 7, 8, all compensated rectifier circuits are without the main rectifier capacitor. All of the compensated rectifier circuit compensation accumulator capacitances are chosen equal to the simple rectifier capacitance, this way the load curves shown in Fig. 9 and 10 are comparable.

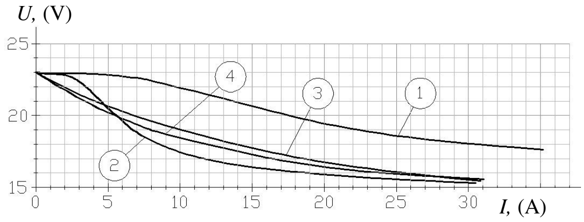

Fig. 9. **Load characteristics of rectifiers *(PSIM)***

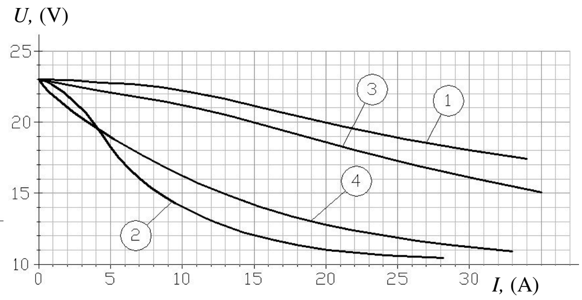

Fig. 10. **Load characteristics of rectifiers *(Multisim)***

Estimating the load curves displayed in Fig. 9 and 10 it can be seen that the characteristics 1 and 2 have a critical value of the load to which they provide a very stable voltage – 1st curve to ~ 5 A, but 2nd curve ~2 A. It follows that the compensated rectifier with additional elevated voltage rectifier and capacitance shown in Fig. 7 gives the highest efficiency. Shown in Fig. 6 – the circuit single-phase rectifier with the voltage doubler – the efficiency is lower, the load curve provides a stable voltage to the load current value of 2 A, and more increasing current value of the load voltage drop becomes fastest of all the reference rectifier options, and the circuit negative characteristic is its complex construction.

The compensation rectifier circuit in Fig. 8, the load curve 3rd in Fig. 9 and 10 is similar to that of a simple rectifier with the capacitance filter circuit and the load curve 3rd in Fig. 9 and 10 the output average voltage value decreases in all areas where the output current average value is rising.

Conclusions

1. A simple rectifier with the filter capacitance load curve is decreasing at any load current rise in the range.
2. Any compensated rectifier circuit option load curves are less dropping comparing to the simple rectifier's with the capacitive filter load curve. The compensated rectifier with the additional elevated-voltage rectifier bridge and storing capacitance in a certain range of the load current rise-the time voltage value remains constant.
3. The most effective compensated rectifier option is the circuit with the elevated-voltage rectifier bridge and accumulator capacitance, its load curve shows the best characteristics of the voltage source among the observed circuits, as well as the technical construction is simple.

Acknowledgements

The study has been produced with the support of the project: Cross border JRTC, Interreg LAT-LIT, No: LV-LT/1.1./LLII-061/2010/

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