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Active Compensation for a Driving System with Chopper and DC Motor

***Abstract**. The paper deals with the behaviour of a load consisting of an uncontrolled rectifier + chopper + DC motor at the supplying from the AC line. The effect of a power active filter over the current absorbed by motor from the AC line (of approximately 100 A rms) is revealed by experimental data. The necessity to protect the DC motor is underlined. A stand with a schema for energy recovering identical to that used for a real driving system from a tram was used. The difference between the active compensation from a tram and its counterpart from the transforming substation AC/AC 20kV/0.4 kV is presented.*

***Streszczenie.** W artykule analizowany jest wpływ obciążenia w systemie z prostownikiem, chopperem i silnikiem DC. Zbadano eksperymentalnie wpływ aktywnego filtru. Rozważano przypadek zbliżony do zasilania sieci tramwajowej. **Aktywna kompensacja mocy w systemie napędowym z silnikiem DC**.*

Keywords: Driving system with chopper and DC motor; harmonics active compensation; schema with regenerative braking.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

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Introduction

Generally the load compensation represents a complicated problem, especially in the presence of frequent load changes resulting into non-sinusoidal regimes within the network [1]-[5]. The full load compensation assumes 3 processes with different theoretical fundamentals but practically interdependent to each other. At theoretical level the compensation problem is concerned with:

a) The elimination of non-symmetries that occur at load currents when supplying with symmetrical voltages.

b) The elimination (diminishing up to values accepted by quality standards) of the currents' superior harmonics (we will address them as SH), theoretically absorbed by the load. But the active power flows along certain SH might have senses opposite to the sense of the active power along the fundamental harmonic (both load and power supply can be affected by this phenomenon).

c) Improving the power factor along the fundamental harmonic, up to a value accepted by the quality norms (higher than the neutral power factor - usually 0.92).

Each stage defined at theoretic level might have a correspondent in practice, providing that the problem is separately approached for each of the mentioned deficiency, in a different manner:

- getting the symmetry for circuits (networks) that operate in non-symmetric regime is performed by means of some three-phase circuits in the so called "Steinmetz" connection – the technique being valid at operation in sinusoidal regimes with constant network frequency;
- removing the superior harmonics through passive, active or hybrid filtering, practically reducing the non-sinusoidal regimes of currents (and of voltages across the terminals respectively) up to values accepted by the network to which the load is connected [6]-[10];
- improving the power factor along the fundamental harmonic by means of capacitor banks in fixed or variable configurations (for inductive loads), respectively through the use on nonlinear coils (for capacitive loads).

Filter for harmonic limitation

Some matters must be clarified with respect to filters. Do the filters (passive, active or hybrid) improve the non-symmetric regime? Do they also influence the power factor along the fundamental harmonic? Considering their specific behaviour, the answers to these questions must be carefully analyzed. When the limitations over the non-symmetries introduced by load are addressed, obviously they will not act as a Steinmetz connection. Instead they will contribute to the non-symmetry reduction, as long as the effects of the superior harmonics introduced by load might have effects similar to the non-symmetry. This happens because the current harmonics multiple of $(3k+2)$ form negative systems of currents. Their diminishing results into the reducing of the non-symmetric regime for current harmonics introduced by load for the negative current sequences. On the other hand, the current harmonics multiple of $3k$ form zero systems of currents. Their diminishing results into the reduction of the non-symmetric regime for the current harmonics introduced by load for the zero current sequences [5].

An analysis of filters' impact over the power factor reveals that a common approach is to consider that the active filters improve it. The assumption relies on the theory of real and imaginary instantaneous powers, and might be correct providing that a definition for this factor might be conceived [6], [11]-[14].

In the specialty literature this problem is usually treated through the assimilation of the power factor improvement with the phase-difference between voltage and current along the fundamental harmonic. This is actually a consequence of another theory that provides a definition for the power factor. Here the problems might be discussed at theoretic level but the improvement of the power factor means above all the specification of a range for its values – as it is considered a power quality parameter [15,16].

Harmonics reduction might result into the power factor's improvement along the fundamental harmonic (e.g. through the limitation of power flows along the superior harmonics of voltages and currents). But this is not enough – the schedule for the active filter's activity must be provided too.

Another technical problem from practice is related to the entities protected through filtering. In all cases it is compulsory to protect the network to which the load is connected against the superior voltage and current harmonics induced by the load in the network. For this aim, harmonic currents corresponding to *SH*s are generated locally and are meant to flow from filter to load such as to force the load to take over from filter these additional currents (relative to the current along the fundamental harmonic). This technique does not provide any protection to load. Therefore other methods must be imagined for its protection, mainly in order to improve its lifetime [17].

Another technical problem faced during the utilization of electric filters is related to the consequences of the generation of desired harmonic currents (obeying quality standards) which still include harmonic components, of smaller weights. For these situations might be more appropriate to consider the power flows – because it is possible to find significant power for certain harmonic orders, which might create problems related to the electromagnetic interference with other loads from vicinity.

Finally one must consider the sequence of actions to be scheduled when both the power factor improvement and harmonics reduction may be obtained through the active filter control. The answer is simple – because many theoretical demonstrations proved that the simple introduction of banks of capacitors for compensation may result into the regime's worsening instead of its improvement if the load absorbs non-sinusoidal currents [2]. Therefore it is recommended to firstly reduce the harmonics through filtering, followed by the power factor improvement along the fundamental harmonic.

Three-phase load based on an un-controlled rectifier and a DC motor

The supplying schema is depicted by Fig. 1. The three-phase load consists of a three-phase load – formed from the un-controlled rectifier with diodes, the step-down chopper and the DC motor. An asynchronous generator is placed along the motor's axis. It takes over the energy from the regenerative braking processes of the DC motor. The load is supplied from the AC network through a step-down transformer 20 kV/0.4 kV (MV/LV).

A complex data acquisition system is placed between transformer and rectifier [20]. It provides monitoring and processing of data and was employed to record and process the voltages and currents absorbed by load.

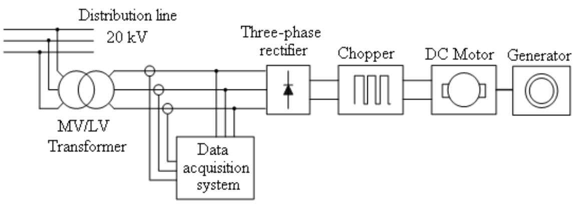

Fig.1. Simplified schema of the three-phase supplying system MV/LV transformer – DC load used on stand

Based on this schema more sets of recordings were acquired for various loads of the DC motors. The processed data made possible the determination of spectral components of the active and reactive powers.

Fig. 2 depicts the waveforms of voltages and currents recorded for a current flowing through motor with a rms value of 100 A.

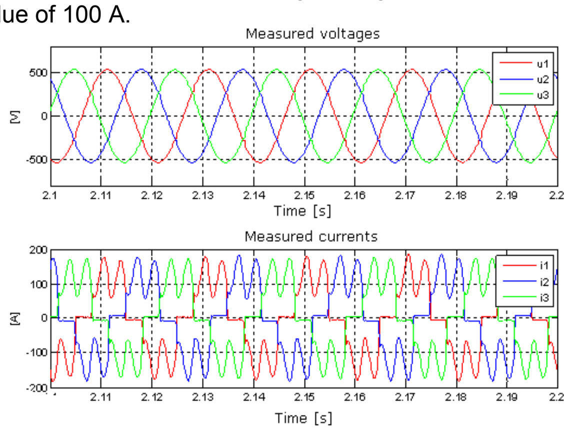

Fig. 2. Voltages and currents waveforms registered with the data acquisition system from Fig. 1

Based on the acquired data and using an original decomposition algorithm – based on Fast Fourier Transform (FFT) [21], decompositions in Fourier series were performed. The results of these decompositions are depicted by Fig. 3 and by Table 1 – for voltages and Table 2 – for currents, for the most significant harmonics. Based

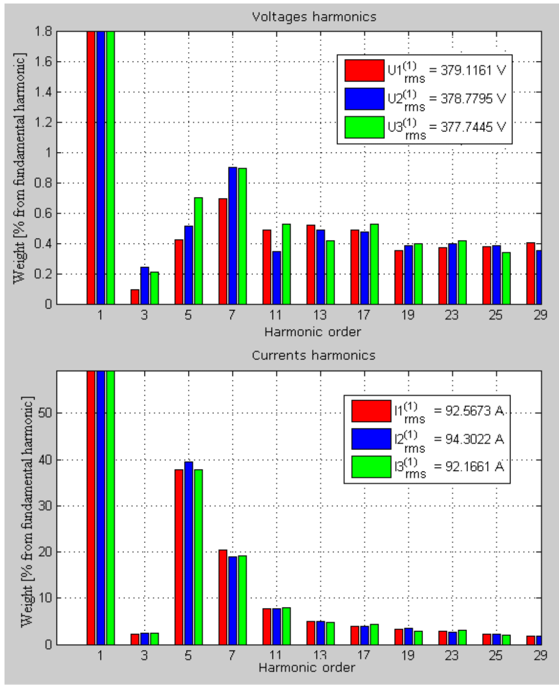

Fig. 3. The first 29 harmonics calculated with FFT for voltages (up) and currents (down)

on them the following quantities were determined:

- The phase voltages RMS values:

$V_{1_{rms}}$ = 379.17 V; $V_{2_{rms}}$ = 378.84 V; $V_{3_{rms}}$ = 377.81 V

- The total harmonic distortions of the phase voltages:

$VTHD_1$ = 1.63 %; $VTHD_2$ = 1.75 % ; $VTHD_3$ = 1.87 %

- The phase currents RMS values:

$I_{1_{rms}}$ = 101.35 A; $I_{2_{rms}}$ = 103.59 A; $I_{3_{rms}}$ = 100.69 A

-The RMS values for the fundamental harmonic:

$I^{(1)}_{1\text{-}rms}$ = 92.57 A; $I^{(1)}_{2\text{--}rms}$ = 94.3 A; $I^{(1)}_{3\text{-}rms}$ = 92.17 A

- The total harmonic distortions of the phase currents:

$ITHD_1$ = 40.72%; $ITHD_2$ = 41.39%; $ITHD_3$ = 40.27%.

The harmonic decompositions can be performed for high harmonic orders too, but the runtime involved increases with the harmonic order.

Considering the standards used as reference for the time being (the IEEE 519/1992 standard [24]), the maximum harmonic order selected for decomposition is 50. Fig. 3 depicts data for the first 29 harmonics from the decompositions of voltages and currents.

The upper limit for the harmonic number was selected based on the minimum weight with respect to the fundamental harmonic (1%). Moreover, these harmonics are relatively important for the determination of power flows for various spectral components of powers (along superior harmonics).

The harmonic decompositions of voltages and currents made possible the determination of the spectral components of the active and reactive powers [22]. They are depicted by Fig. 4. The total values of these powers were computed as:

S = 115.716 kVA; *P* = 104.968 kW;

Q = 12.732 kVAr; *D* = 46.990 kVAd.

The power factor was evaluated as *PF*=0.907 (with an inductive character).

Using an active filter

The analyzed schema with an active filter connected in the load vicinity is depicted by Fig. 5. It was implemented on the stand used to test the driving system of the DC motor from a tram supplied by means of a step-down chopper from the three-phase rectifier with diodes. An active filter of type shunt was used in order to reduce the effects of the harmonic currents introduced in the supplying network by the full load (rectifier + chopper + DC motor). The complex data acquisition system is placed before the active filter. It provides monitoring and processing of data and was employed to record and process the voltages and currents absorbed by the load, using the active filter.

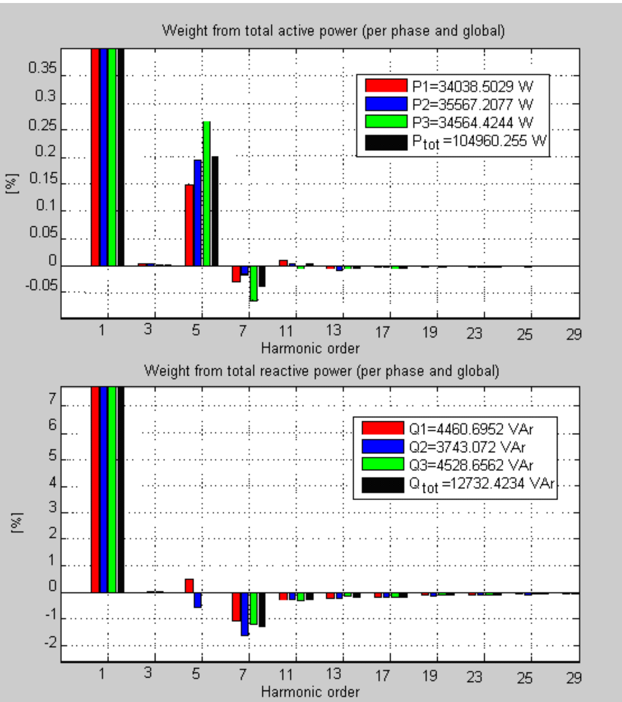

Fig. 4. Spectral components of the (re)active powers, absorbed from the supplying source, before compensation

Fig. 6 depicts the waveforms of voltages and currents recorded for a phase current flowing through motor with a rms value of 100 A.

The results of the decompositions, using FFT are depicted by Fig. 7. The spectral components of the active and reactive powers are depicted by Fig. 8.

The harmonic decompositions of the voltages and currents allowed the determination of the spectral components of the active and reactive powers. The total values of these powers are:

S = 115.617 kVA*; P* = 115.227 kW*;*

Q = 7.370 kVAr; *D* = 5.934 kVAd.

The power factor in this case was calculated as: *PF* =0.996 (with an inductive character).

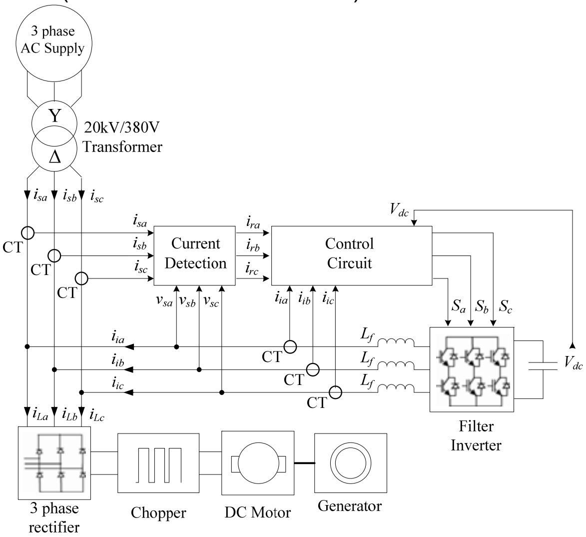

Fig. 5. Test schema with an active filter of type shunt

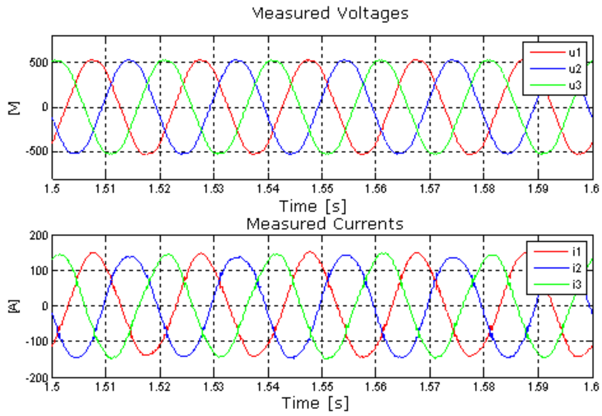

Fig. 6. Waveforms for the schematic of Fig. 5

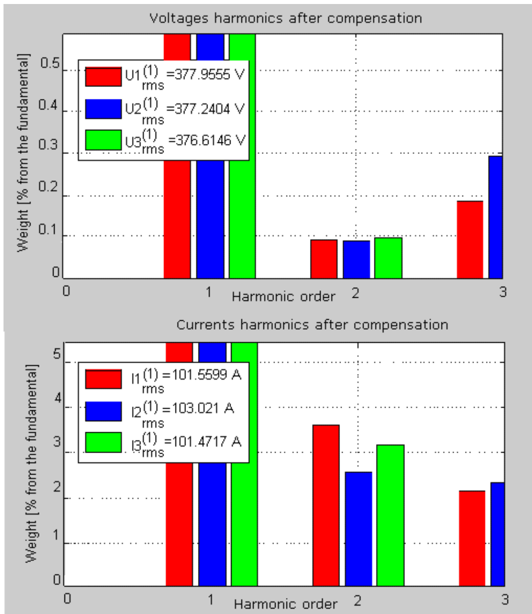

Fig. 7. The main harmonics components calculated with FFT for voltages (up) and currents (down) – after compensation

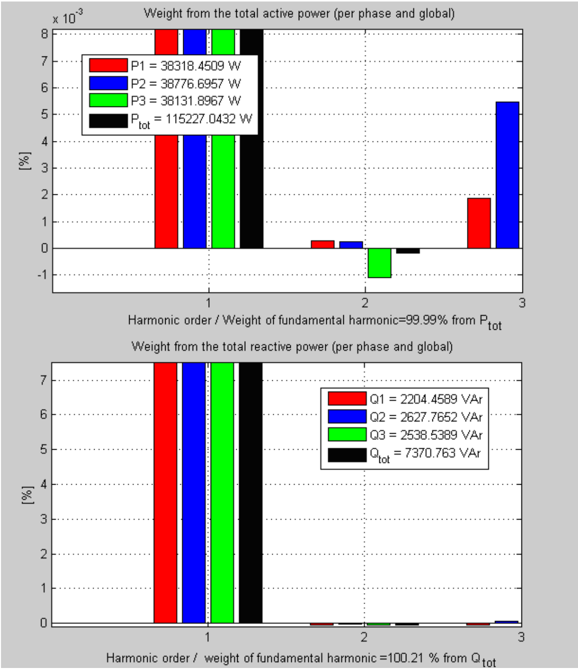

Fig. 8. Spectral components of the (re)active powers, absorbed from the supplying source, after compensation

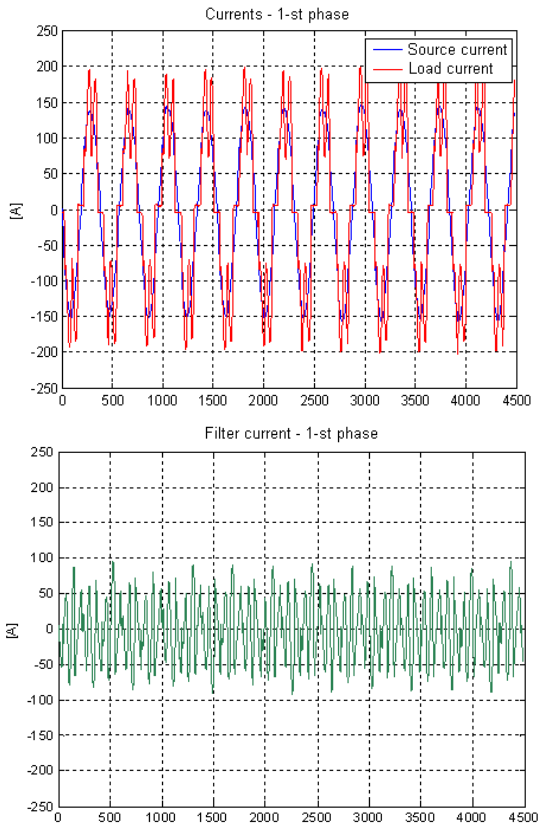

Fig. 9. The currents through source and load (up) and difference of currents (down) – after compensation, for the 1-st phase

Currents Through Active Filter

Considering the waveforms of the currents through the load before the compensations and after the use of the active filter one could determine the currents through every phase. For the first phase these currents are depicted by Fig. 9 (up - the source current and the current absorbed by the load and down - the difference between both currents).

The currents through filter exhibit significant distortions. They do not include the fundamental harmonic. Considering the active powers for both situations one can see that for almost the same apparent power absorbed by load with or without filter, through the use of active filter, the active power absorbed from the AC network is increased with 10.259 kW. This, reported to the AC network without filter represents an increase of 9.77%. This additional power is made on the basis of the distorting power decrease from 46.990 kVAd to 5.934 kVAd, being related to that part of the calculation corresponding to the cross-over harmonics (different harmonic orders for voltages and currents). The power factor's improvement in this case is significant, as it rises from 0.907 to 0.996 (preserving its inductive character). The diminishing of the absorbed reactive power is not so dramatic (it is necessary for the DC motor), proving that in fact the power flows in such situations must be evaluated in a global manner and correlated to each other.

Conclusion

The compensation with active filters of type shunt provides conditions for the protection of the source which supplies the load formed from the three-phase un-controlled rectifier, step-down chopper and DC motor.

The harmonic distortions of the currents for this type of loads, according to the IEEE 519/1992 standard, must be lower than 8% for the phase currents [24]. In the analyzed case they were $ITHD_1$ = 5.14%; $ITHD_2$ = 4.36%; $ITHD_3$ = 5.11%, so they obeyed the standards for power quality. Despite all these, the standards do not specify threshold values for the powers absorbed by load along *SH*s.

An interesting aspect is related to the influence of filter when placed in the substation used to supply with electric power the analyzed equipment. A series of experimental data along with simulations made with MATLAB/SIMULINK [17], [19] proved that, from the currents harmonic distortions point of view, the phenomena present similarities if along the supplying line in DC there are only few active transportation equipment with electric driving. Yet in this case too the filter will protect only the AC network against the current harmonics coming from the three-phase load.

Many vehicles used for urban transportation are supplied from the three-phase un-controlled rectifier, placed in the transformation substation of the DC line. In this case no discussion is made with respect to powers – only the harmonic currents being considered. In all cases, the quality of the power/energy must be discussed in parallel with the harmonic distortions of voltages and currents and with the spectral components of powers.

Although the differences between the values of total apparent and active powers respectively, after compensation, are not significant, the non-zero values of reactive and distorting powers yield the conclusion that the discussion on energy/power quality must address the powers too. Even if they might compensate mutually, their presence may cause unpleasant effects over the network from which the DC line is supplied.

Other future work should be concerned with the additional powers still remaining after the compensation. The harmonic currents' limiting to some imposed ranges does not represent the solution for all problems related to the quality of energy/power in the electric networks. It is compulsory to correlate these standards with problems of Electromagnetic Interference (EMI) at low frequencies.

Considering the shape of currents absorbed by load (Figs. 2 and 6), both represented in Fig. 9, it is clear that the protection provided by the filter will be noticed only at the level of the supplying network (or substation of transformation). The filter does not protect the load! To protect, for example, the DC motor, other measures should be taken in order to increase the lifetime of a DC motor.

Table 1. Significant Initial Phases, Magnitudes and Weights Relative to the Fundamental Component of Voltages

	V_1			V_2			V_3		
Harm. order	Mag.[V]	Initial Phase deg]	Weight[%]	Mag.[V]	Initial Phase [deg]	Weight [%]	Mag. [V]	Initial Phase [deg]	Weight [%]
1	379.12	-111.1	100	378.38	128.79	100	377.74	8.76	100
5	1.59	-60.58	0.42	1.94	22.17	0.51	2.65	162.55	0.7
7	2.63	65.3	0.48	3.41	-48.29	0.9	3.37	179.2	0.89
11	1.84	90.1	0.49	1.31	-159.89	0.34	1.98	-47.53	0.52
13	1.96	-130.77	0.52	1.85	99.62	0.47	1.57	-9.93	0.42
17	1.85	-88.36	0.49	1.81	31.66	0.47	1.99	151.18	0.52
S19	1.34	55.83	0.35	1.45	-57.21	0.38	1.49	178.14	0.39
23	1.4	103.66	0.37	1.49	-133.63	0.39	1.57	-10.86	0.41
25	1.42	-108.58	0.37	1.47	128.62	0.38	1.29	10.67	0.34
29	1.54	-41.46	0.4	1.33	78.36	0.35	1.63	-167.3	0.43

Table 2. Significant Initial Phases, Magnitudes and Weights Relative to the Fundamental Component of Currents

	I_1			I_2			I_3		
Harm. Order	Mag.[A]	Initial Phase [deg]	Weight[%]	Harm. Order	Mag.[A]	Initial Phase [deg]	Weight[%]	Harm. Order	Mag.[A]
1	92.67	-185.53	100	1	92.67	-185.53	100	1	92.67
5	34.62	-82.9	37.77	5	34.62	-82.9	37.77	5	34.62
7	18.95	167.26	20.48	7	18.95	167.26	20.48	7	18.95
11	7.09	165.19	7.66	11	7.09	165.19	7.66	11	7.09
13	4.57	-27.8	4.94	13	4.57	-27.8	4.94	13	4.57
17	3.69	11.52	3.98	17	3.69	11.52	3.98	17	3.69
19	2.98	158.23	3.23	19	2.98	158.23	3.23	19	2.98
23	2.63	-149.11	2.84	23	2.63	-149.11	2.84	23	2.63
25	1.96	-8.79	2.12	25	1.96	-8.79	2.12	25	1.96
29	1.74	51.39	1.88	29	1.74	51.39	1.88	29	1.74

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