HARMONICS IN HIGH VOLTAGE NETWORKS

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Abstract: The paper presents the results of studies in the area of harmonics in HV networks that were obtained at the Siberian Energy Institute. The studies have been performed based on the method of harmonic distortion powers that was developed at the Siberian Energy Institute. It contains the notions of distortion power generation and absorption. The method forms the basis of the software package "Harmonics" that is applied for calculation, analysis and study of the harmonic modes in networks of a complicated configuration. The probabilistic mathematical models of loads are suggested. The probabilistic approach to calculation of harmonic modes in the HV network is considered. High levels of harmonics are typical of the nodes with a lower value of the distortion power absorption. The harmonic voltage levels can be normalized in both operating and planned networks of a complicated configuration in a centralised way.

Keywords: Harmonics, harmonic analysis, distortion power, probabilistic mathematical model

I. INTRODUCTION

The 110-220 kV networks are extended and have a great number of connected large consumers such as aluminium plants, railroads. In accordance with the current standards in Russia the normal allowable value of the total harmonic distortion for 220 kV networks is equal to 2 per cent of the nominal voltage, the maximum voltage is 4 per cent, the allowable level of harmonic voltage components of harmonics accounts for 2 per cent. Measurements of the parameters of harmonic modes in 220 kV networks of the Irkutsk electric power system which were performed in 1983-1993 showed that the values of total harmonic distortion and the harmonic voltage levels for many nodes exceeded the allowable levels. The harmonic operating conditions are analysed by the devised method of distortion powers. The properties of harmonic networks are studied, an approach to normalization of harmonic network operation is devised. The results of measurements also show that harmonic currents and voltages are nonstationary and asymmetrical in phases. Mathematical models of loads have been constructed to take into account an asymmetrical probabilistic nature.

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II. METHOD OF DISTORTION POWERS

The method of distortion powers applies the calculation of harmonic conditions in the electric network in the current values that is widely used in Russia and abroad [1, 3]. The condition is calculated for each harmonic separately. Nonlinearity of nodes are modeled by the sources of current, the values and phases of which can be adjusted during calculation as a function of parameters of the node, to which the non-linear load is connected. In this method the electric network and consumer with respect to node i on the n-th harmonic are represented by the equivalent two-pole elements consisting of parallel connected sources of current, conductance and susceptance (Fig.1).

The balance of currents is observed in node i on the n-th harmonic, i.e. generation of currents by their sources to node i is equal to the currents absorbed by nodal admittances

$$\sum_{j=1}^{m} I_{gjin} + I_{ghin} = \left(I_{asgin} + I_{ahgin}\right) + j\left(I_{asrin} + I_{ahrin}\right) \tag{1}$$

The letters used in the indices are: g - generator, a - absorption, s - network, h - load, g - active, r - reactive, i - number of node to be analyzed, n - number of harmonic. The balance of distortion powers which is obtained by multiplying the currents of the n-th harmonic by the nodal nominal voltage U_1 corresponds to the balance of currents

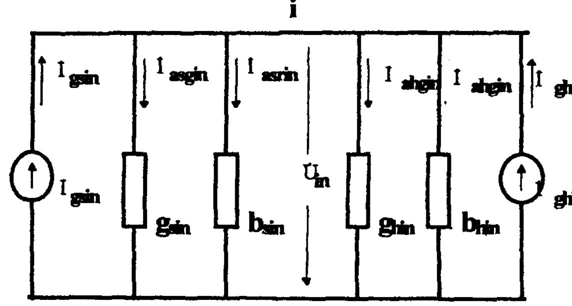

Fig.1.Equivalent circuit of the network and consumer by the method of distortion power balance

of the n-th harmonic of the node in expression (1).

The nodal voltage expressed by the distortion powers is determined as (2)

$$U_n = U_{cn}\frac{\left|\sum_{j=1}^{m}\dot{D}_{gsjin}+\dot{D}_{ghin}\right|}{\left|\left(\dot{D}_{asgin}+\dot{D}_{ahgin}\right)+j\left(\dot{D}_{asrin}+\dot{D}_{ahrin}\right)\right|}, \quad (2)$$

where $\dot{D}_{gsjin} = U_1\dot{I}_{gjin}$, $\dot{D}_{ghin} = U_1\dot{I}_{ghin}$ - generation of the distortion power (GDP) to node i by the nonlinear load of the network that is located in node j and in node i; U_{cn} - admissible value of the harmonic voltage; $D_{asgin} = U_1 U_{cn} g_{sin}$, $D_{ahgin} = U_1 U_{cn} g_{hin}$ - absorption of the distortion power (ADP) by the conductances of the network and load in node i; $D_{asrin} = U_1 U_{cn} b_{sin}$; $D_{ahrin} = U_1 U_{cn} b_{hin}$ - absorption of the distortion power by the susceptances of the network and load in node i.

The total generation of distortion power in the numerator of expression (1)

$$D_{g\Sigma jin} = \left|\sum_{j=1}^{m}\dot{D}_{gsjin}+\dot{D}_{ghin}\right| \quad (3)$$

is of random character and can be calculated by different methods. First, distortion powers can be assigned by magnitudes and phases, second, by mean values and standard deviations of the magnitudes and phases and, third, they can be represented by mathematical models as polynomials, reflecting a probabilistic nature of power variation and played by the Monte-Carlo method. Choice of the representation form for distortion power generation depends on the purpose of calculation. In order that the harmonic voltage level did not exceed the specified value when connecting consumers to the network node, the following condition should be satisfied:

$$\left|\left(D_{asgin}+D_{ahgin}\right)+j\left(D_{asrin}+D_{ahrin}\right)\right| \geq D_{g\Sigma jin} \quad (4)$$

Possibility for maintenance of the studied the harmonic voltage levels in the node, when the value of the resulting generation of the distortion power changes during operation, is reflected by the reserve (margin) value with respect to the absorption of distortion power D_{rain}

$$D_{rain} = \left|\left(D_{asgin}+D_{ahgin}\right)+j\left(D_{asrin}+D_{ahrin}\right)\right| - D_{g\Sigma jin}. \quad (5)$$

The harmonic voltage level in the nodes of power systems is determined primarily by the large non-linear loads. Contribution of the non-linear load allocated in node j of the network to voltage of the n-th harmonic of node i is equal to

$$U_{jin} = U_{cn}\frac{\left|D_{gsjin}\right|}{\left|\left(D_{asgin}+D_{ahgin}\right)+\left(D_{asrin}+D_{ahrin}\right)\right|}. \quad (6)$$

When contribution of a nonlinear load is determined, the value of distortion power generation D_{gsjin} of load is determined by the mean harmonic current value.

Connection of a consumer to a system can lead to the resonance of susceptances of the network and consumer, when the total value of distortion power absorption by susceptances becomes equal to zero.

From the condition

$$D_{asrin} + D_{ahrin} = 0, \quad (7)$$

that corresponds to the resonance of nodal susceptances the resonant voltages in node i are calculated

$$\dot{U}_{rin} = \frac{\dot{U}_{cn} D_{g\Sigma jin}}{D_{asgin} + D_{ahgin}}. \quad (8)$$

Resonance voltages are calculated for the mean values of distortion power generation.

The resonant capacity of a battery of capacitors Q_{pin} determined by condition (7) is equal to

$$Q_{rin} = Q_i - \left(D_{asrin} + D_{ahrin}\right)/\left(n\dot{U}_{cn}\right), \quad (9)$$

where Q_i - capacity of a battery of power factor correction capacitors in node i; $\dot{U}_{cn}$ - calculated levels of voltages of the n-th harmonic in p.u.

The devised method was used as a methodological base for creation of the software package "Harmonics". The package "Harmonics" calculates parameters allowing one to estimate the effect on operating conditions of both the network and nonlinear loads.

III. NETWORK PROPERTIES CAUSED BY DISTORTION POWERS

The properties were studied on the scheme with the minimum number of nodes (Fig.2) in which in accordance to the author's opinion properties of bulk power systems are displayed. The scheme of Fig.2 consists of two sections of the single-circuit 220 kV transmission lines of the same length with the wire cross-section of 300 mm. At the current density of 1.1 A/mm the power transmitted over transmission lines accounts for 135 MVA. The network is connected to the large 500 kV node through the 500 MVA autotransformer. In the nodal the harmonic voltage level amount to 1% of the rated voltage of the basic frequency for all the studied harmonics. Consumers are connected to nodes 21, 22 and 23 through the 63 MVA transformers with the secondary voltage of 10 kV.

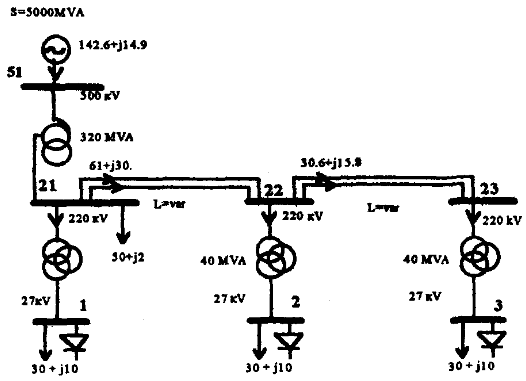

Fig.2. The scheme for studying electric network properties

Fig. 3 presents the values of the total harmonic distortion and the harmonic voltage levels created by harmonics of the system of 500 kV in node 23 as a function of line length change at the nodal loads of 20 MVA (10 MVA of lighting load and 10 MVA of motor one). The levels of the 5-th harmonic voltage for nodes 1, 2, 3, 21, 22, 23 are given in Fig.4.They have a complicated dependence on the line length. These curves show that support of the harmonic voltage levels in the node of system connection (on the 500 kV buses) does not guarantee admissible harmonic levels in the network. The electric network can cause considerable

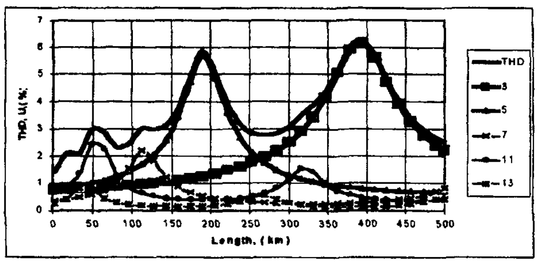

Fig.3 Total harmonic distortion and the harmonic voltage levels in the node 23.

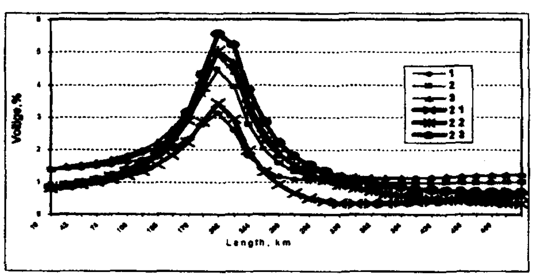

Fig.4. Voltage of the 5-th harmonic in nodes as function in line length

increase in the harmonic voltage levels. Therefore, to provide the admissible the harmonic voltage levels in the network nodes special measures are required. The maximum the harmonic voltage levels are observed at the minimum values of the absorption distortion power of the nodes (Fig.5). Fig. 6 presents distortion power generation of harmonic 5 for the 220 kV transmission line at its different lengths and the same distances between substations. The line feeds 31 substations with a traction load power of 10 MW and a local load power of 15 MW each. In this case the power plants with a capacity of 500 MVA and local loads of 400 MW are connected in nodes 1, 11, 21 and 31. At a line length of 3000 km the distortion power generation from node 29 to node 1 situated at a distance of 2800 km amounts to 50% of the distortion power generation of load in node 1, i.e. the harmonics run to great distances. The calculations have showed that the phenomena observed on the 5-th harmonic are typical of other harmonics as well, however at different line lengths.

IV. NORMALISATION OF OPERATING CONDITIONS OF HIGHER HARMONIC NETWORK

The harmonic operating conditions can be normalized by the following methods as a function of the specific electric network and load powers [2]:

- decrease in generation of the harmonic currents of rectifier loads by increasing the number of ripples and commutation angles;
- installation of filters for harmonic currents in the connection points of large converter units;

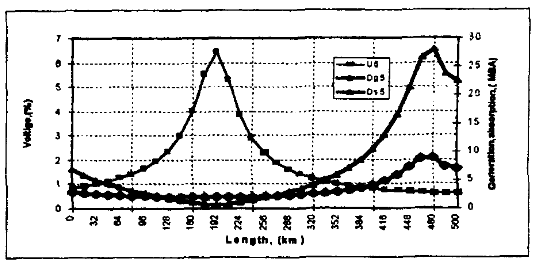

Fig.5. Voltage, ADP, GDP of the 5-th harmonic in node 23 as function in line lengths

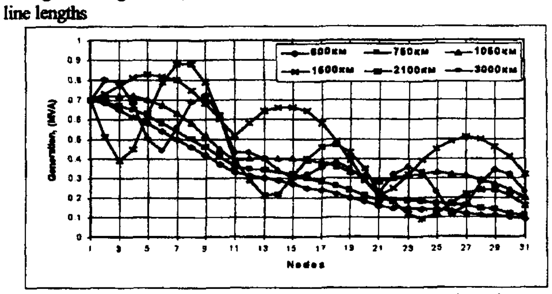

Fig. 6.Distortion power generation of harmonic 5 in node 1 from traction loads at different line lengths

• enhancement of the active absorption in one or several nodes of an electric network with extended transmission lines.

As was shown above, normalization of the operating conditions in the connection nodes is insufficient for their normalization in all network nodes, as far as the extended transmission lines cause the increase in harmonic levels. In these lines to normalize the harmonic operating conditions the use is made of its following properties: high levels of harmonics correspond to nodes with lower generation and absorption levels; change in absorption in one of the nodes, placed on the extended line, results in change in the harmonic voltage in other nodes. The indicated features make it possible to normalize the harmonic operating conditions in a great number of nodes of an extended line by increasing the active absorption with the help of low-capacity resonance installations (Fig.7).

Installation of three absorption devices for 5-th harmonic with an absorption capacity of 2 MVA in three nodes at a distance of 250, 750 and 1250 km from the feeding station has normalized the harmonic level along the whole line 1500 km long (compare curves U5, U5-f). Absorption being increased by connecting the resonance installations in nodes with the minimum absorption, the voltage of 5-th harmonic decreases more than threefold along the whole line. One device with a capacity of 2-4 MVA allows normalization of the harmonic operating conditions of the line 300-1000 km long depending on specific features of a concrete network. About 2 MVA of the power of cosine capacitors is required per 1 MVA of the distortion power absorption.

V. MODELLING OF DISTORTION POWER GENERATION OF NONLINEAR ASYMMETRICAL LOADS

Accuracy of calculations of the harmonic operating conditions in 110-220 kV networks depends to a great extent on the precise modelling of distortion power generation of the largest nonlinear loads. The results of daily measurements of harmonic modes which are taken every minute by the software package "Omsk" for example, may be applied for model construction. The main nonlinear loads of 110-220 kV networks are traction substations of the railways and aluminium plants. Below a mathematical model for the distortion power generation of traction load is given for illustration. Measurement of the harmonic operating conditions for traction loads shows that the harmonic currents are asymmetrical and change steadily in wide ranges because of addition of currents from several electric locomotives, powered from the substation on the railway section 60-80 km long (Fig.8).

Processing of measurements of parameters on the harmonic operating conditions allows the probabilistic mathematical model for distortion power generation of load, connected to the substation, to be obtained. Distortion power generation of harmonics is determined by the active load power and caused by the consumer's technology.

Distortion power generation of the nonlinear asymmetrical load to calculate harmonic operating conditions is represented by the expression:

$$\dot{D}_{knm}=\dot{D}_{knc}(1+R_m(x_{pm}))(1+R_{knm}(x_{dkm}))EXP(-j\varphi_{knm}(x_{\varphi km})),$$

where k=1 corresponds to the positive sequence, k=2 corresponds to the negative sequence (in HV networks the levels of zero sequence currents are much lower than the positive and negative sequence currents, therefore the zero sequence currents are not modeled),

m - the number of operating condition from the analyzed sample,

$\dot{D}_{knc}=P_cK_{knc}EXP(-j\varphi_{knc})$ is the mean value of distortion power generation of the n-th harmonic of sequence k,

P_c is the mean daily value of active power,

K_{knc} is the mean daily value of the total harmonic distortion that is calculated as

$$K_{knm} = D_{knm} / P_m ,$$

R_m is the active power deviation for operating condition m from its mean value in p.u. ($R_m = (P_m - Pc)/Pc$) that is represented in the mathematical model as a polynomial of the third power

$$R_m = A_3 x_{pm}^3 + A_2 x_{pm}^2 + A_1 x_{pm} + A_0 ,$$

x_{pm} is a random number,

A_3, A_2, A_1, A_0 are coefficients that are obtained by

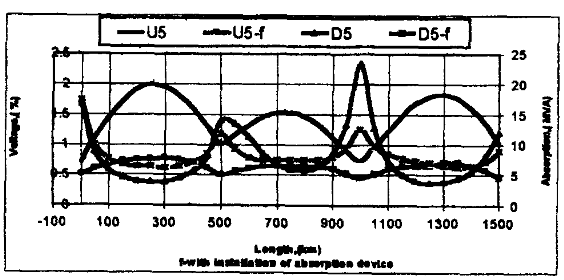

Fig. 7. Change in voltage of harmonic 5 with and without the active absorption devices

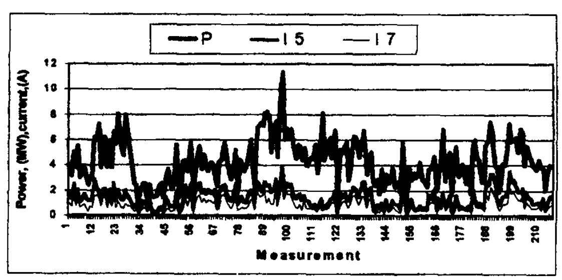

Fig.8. Active power, 5-th and 7-th harmonic currents of load connected to Mysovaya substation.

approximation of the cumulative probability curve R_m, which is constructed based on the results of statistical processing of measurements of the active power,

$R_{knm} = (K_{knm} - K_{knc}) / K_{knc}$ is the relative variation in the value of distortion power generation of the n-th harmonic of sequence k for operating condition m.

In the mathematical model it is taken into account in the form of a polynomial of the third power as

$$R_{knm} = B_{3kn} x_{dkm}^3 + B_{2kn} x_{dkm}^2 + B_{1kn} x_{dkm} + B_{0kn},$$

x_{dkm} is a random number,

$B_{3kn}, B_{2kn}, B_{1kn}, B_{0kn}$ are coefficients that are obtained by approximation of the cumulative probability curve R_{knm}, which is constructed based on the results of statistical processing of measurements on the main and higher harmonic currents,

φ_{knc} is the mean phase value of the distortion power generation of harmonics for the n-th harmonic,

φ_{knm} is the phase deviation from its mean value for the distortion power generation of the n-th harmonic of sequence k. In the mathematical model it is represented in the form of a polynomial of the third power

$$\varphi_{knm} = C_{3kn} x_{\varphi km}^3 + C_{2kn} x_{\varphi km}^2 + C_{1kn} x_{\varphi km} + C_{okn},$$

$x_{\varphi km}$ is a random number,

$C_{3kn}, C_{2kn}, C_{1kn}, C_{0kn}$ are coefficients that are obtained by approximation of the cumulative probability curve, which is constructed based on the results of statistical processing of measured phases of the main and higher harmonic currents.

The higher harmonic operating conditions are calculated by the Monte-Carlo method, in accordance with which load is modeled on the generator of random numbers with the uniform distribution law.

For the one-load model the use is made of 5 samples of random numbers.

If the probabilistic nature of nonlinear loads is considered in a simplified way, the mean values of distortion powers of the higher harmonics and their standard deviations may be applied. The mean values of distortion powers from several sources are determined by the geometrical addition. The mean-root-square sum is found for standard deviations and the values corresponding to the mean value and the value with a 95 % probability are determined from them.

The model of traction load that is constructed for the Mysovaya substation on the East- Siberian railway on the 220 kV transformer side with a capacity of 40 MVA feeding the traction load is given as an example. While modeling the load, 9 main harmonics: 3, 5, 7, 11, 13, 17, 19, 23, 25 were taken into account. Fig. 8 shows a daily variation of the active power and currents for the prevailing harmonics. The mean value of active power is equal to P_c=4.34 MW, the standard power deviation from its mean value accounts for 40.56%. When processing, the distortion power absorption of traction load was taken equal to zero.

From the results of approximation of the cumulative probability of active power deviations in Fig. 9 the random values of power are calculated by the expression

$$R_m = 3.31 x_{pm}^3 - 4.39 x_{pm}^2 + 2.71 x_{pm} - 0.75 \cdot$$

The mean values and the standard deviations of harmonic distortion powers are given in Table 1. The polynomial coefficients approximating the cumulative probabilities of deviations in the harmonic distortion powers from their mean values are presented in Table 2.

The model developed for traction loads is applicable for other load types as well. The polynomial coefficients can be obtained by processing the measurements of parameters of harmonic modes.

VI. CONCLUSIONS

1. The method of distortion powers allows first, the analysis of the harmonic modes for the network nodes, representing formation of the harmonic voltage levels as a result of interaction of 2 processes: generation and absorption of harmonics, and second, the estimation of interaction between the consumer and the electric network, i.e. formulation of consumer requirements to the network, selection of reactive compensators with

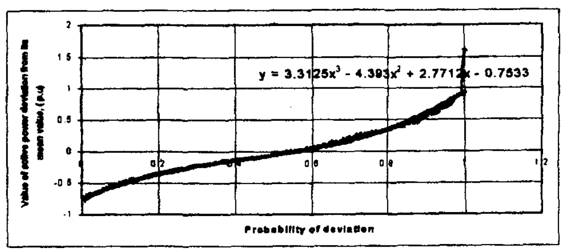

Fig. 9. The cumulative probability of the active power deviation and its approximation by the polynomial of the third power

Table 1

Harmonic	Positive sequence				Negative sequence			
	Power,(%)		Phase(deg.)		Power,(%)		Phase(deg.)	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
3	11.62	3.54	121.92	36.29	14.44	4.74	115.52	31.19
5	5.22	1.96	84.00	65.13	9.68	1.86	-81.21	14.36
7	4.76	1.32	236.02	27.98	4.08	1.19	49.25	41.00

regard to harmonics, estimation of danger from resonance phenomena.

2. Extended transmission lines 110 kV and higher cause the enhancement of harmonic voltage levels. The high levels of harmonic voltages correspond to nodes with small values of distortion power generation and absorption.

3. The generated distortion power of nonlinear loads can spread along the 220 kV transmission lines for a distance of above 2000 km without essential damping.

4. The harmonic operating conditions in the network with extended lines can be normalized by increasing the active distortion power absorption in concrete network nodes with the help of resonance installations with an active absorption power of 2-4 MVA.

5.The traction loads are nonlinear, asymmetrical and nonstationary. The mathematical probabilistic model of traction loads for a node is constructed based on the results of processing measurements of the parameters for the harmonic operating conditions.

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VI. BIOGRAPHIES

Dr. Sergei S. SMIRNOV was born in 1936 in Berendeevo, Russia. He defended thesis of Candidate of Technical Sciences and received the scientific degree. At present he is Researcher in the Siberian Energy Institute in the Russian Academy of Sciences. His field of interest is in higher harmonics.

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TABLE 2
THE POLYNOMIAL COEFFICIENTS APPROXIMATING THE CUMULATIVE PROBABILITIES OF DEVIATIONS IN THE HARMONIC DISTORTION POWERS FROM THER MEAN VALUES

Harmo-nic	Seque-nce	Distortion power					Distortion power phase				
		D_{mean}	Polynom. coefficients				Phase	Polinom. Coefficients			
		%	B3	B2	B1	B0	degr.	C3	C2	C1	CO
3	1	11.62	2.53	-3.22	2.03	-0.58	121.5	0	0	105.13	-52.81
	2	14.44	2.53	-3.22	2.03	-0.58	115.5	0	0	105.13	-52.81
5	1	5.22	2.75	-4.24	3.04	-0.8	83.9	-72.4	73.9	190.4	-99.8
	2	9.69	2.6	-3.97	2.27	-0.46	-81.2	124.4	-217.9	154	-35.63
7	1	4.76	2.63	-4.81	3.35	-0.73	236	464	-773	438	-77.4
	2	4.08	2.84	-4.35	3.35	-0.73	49.3	188.6	-273.8	244.4	-78
11	1	1.59	2.93	-4.12	3.1	-0.91	-4	220	-419	528	-180
	2	2.41	3.39	-5.56	3.48	-0.73	177	665	-1025	542	-96
13	1	1.44	3.82	-6	-3.79	-0.85	4	1015	-1423	699	-130
	2	1.36	3.82	-6	-3.79	-0.85	246	1057	-2064	1415	-285
17	1	0.95	4.22	-6.17	3.82	-0.91	0.3	0	0	350	-176
	2	0.99	4.22	-6.17	3.82	-0.91	26.8	504	-944	782	-283
19	1	1.08	5.11	-7.01	3.97	-0.93	-24	-107	-88	563	-225
	2	1.7	5.11	-7.01	3.97	-0.93	25	635	-879	584	-158
23	1	1.15	7.57	-8.78	4.02	-0.58	5.9	0	0	328	-160
	2	0.84	7.57	-8.78	4.02	-0.58	-5.3	0	0	328	-160
25	1	0.96	5.89	-7.15	3.78	-0.98	12.7	-583	748	185	-197
	2	0.57	5.89	-7.15	3.78	-0.98	-14	-3.8	190	175	-151