Nonlinear Limiting Resistor (Limistor) – Application in 500kV Power System

I. Ye. Naumkin, D. V. Kochura, L. I. Sarin

***Abstract* -- Description of a new nonlinear power resistor is presented. This resistor has linear characteristics up to a certain voltage. Then, its resistance decreases sharply, thus limiting the resistor voltage. Such resistor is called limiting resistor or limistor. Features of a limistor and conditions of its operation are presented. It is shown in the paper that limistor is a new element for the whole power system with its own features in the scope of proper choice and application.**

The paper presents limistor application in a 500 kV system that helps solve an important problem – to provide breaking capacity of SF6 circuit breakers when switching compensated power lines. Connection of a resistor into a circuit of shunt reactors is used as an efficient method for damping a DC component through a circuit breaker.

***Keywords*: nonlinear resistor, compensated power lines, shunt reactor, DC component, breaking capacity of circuit breaker.**

I. Introduction

Power engineering is based on utilization of power equipment, which is generally inductive, capacitive or resistive. Resistors are important elements of electrical circuits as generators, transformers and capacitors.

Resistors are characterized by their target purpose to be operated under abnormal conditions of a network to damp electromagnetic transients. Widely known resistive equipment includes linear power resistors [1] and surge arresters [2].

Description of a new nonlinear power resistor is presented. This resistor has linear characteristic up to a certain voltage value (in particular, in the range from a maximum operating voltage to a short-time permitted voltage). Then, its resistance decreases sharply, thus limiting the resistor voltage. This instantaneous voltage value when the resistor current-voltage characteristic bends is called limiting voltage. And such resistor is called a limiting resistor (limistor) [3]. An example of current-voltage characteristic of a limiting resistor is shown in Fig. 1. The resistance versus voltage characteristic of a limistor is shown in Fig. 2.

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia, June 15 – 18, 2015.

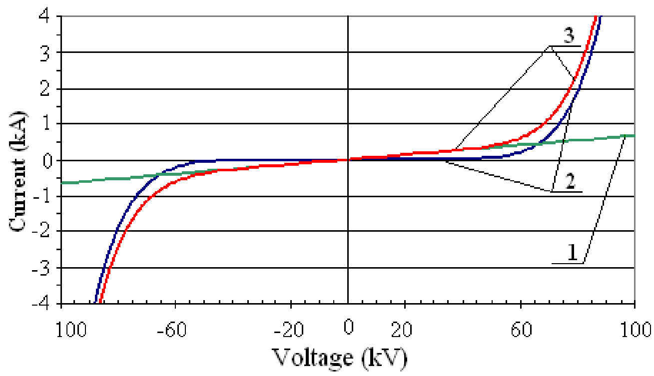

Fig. 1. Current-voltage characteristic of a limistor
1 – i_{lin}, 2 – i_{nonlin}, 3 – i_{lim}

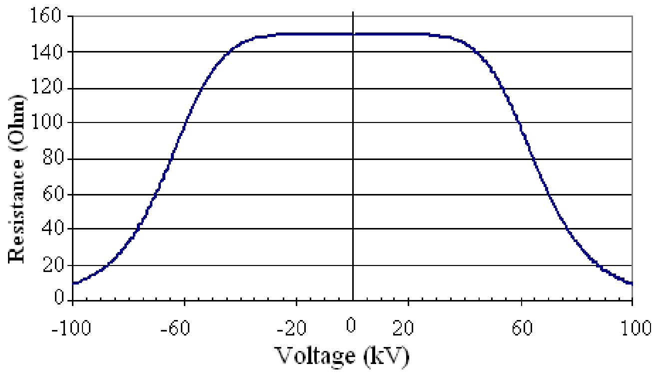

Fig. 2. Resistance versus voltage characteristic of a limistor

Features of limistor and conditions of its operation are presented. It is shown, that limistor becomes a new element for the power system with its own features in the scope of proper choice and application. Heterogeneous design of a limistor is reviewed.

II. Technical Parameters of Limistor

Resistance of the nonlinear limistor part R_{nonlin} is much higher than resistance of its linear part R_{lin} under normal operating conditions of the network (when the limistor voltage $u(t) \le u_m$, where u_m – peak value of maximum operating phase-to-ground voltage):

$$R_{nonlin} = \zeta \cdot R_{lin}, \quad \zeta >> 1. \tag{1}$$

When limistor voltage exceeds some certain value, for example the maximum operating phase-to-ground voltage

$$u_{\lim} = \eta \cdot u_m \tag{2}$$

(in particular case $1 < \eta < 2$), resistance of the nonlinear limistor part R_{nonlin} becomes equal to the resistance of its linear part R_{lin}:

$$R_{nonlin} = R_{lin} \,. \tag{3}$$

The power-law current-voltage characteristic for the nonlinear limistor part

$$u_{nonlin} / U_b = \left(i_{nonlin} / I_b\right)^{\beta} \tag{4}$$

determines resistance of the nonlinear part as

$$R_{nonlin} = R_b \left(U_b / u_{nonlin}\right)^{1/\beta - 1} . \tag{5}$$

It follows from (1) – (5), that the power index of the current-voltage characteristic for the nonlinear limistor part β should satisfy the following:

$$\beta = \frac{\ln \eta}{\ln \eta + \ln \zeta} \,. \tag{6}$$

Values of β are presented in Table 1.

TABLE 1 – POWER INDEXES OF CURRENT-VOLTAGE CHARACTERISTIC FOR NONLINEAR LIMISTOR PART

ζ	η				
	1.2	1.4	1.6	1.8	2
10	0.073	0.127	0.170	0.203	0.231
20	0.057	0.101	0.136	0.164	0.188
30	0.051	0.090	0.121	0.147	0.169
40	0.047	0.084	0.113	0.137	0.158
50	0.045	0.079	0.107	0.131	0.151
60	0.043	0.076	0.103	0.126	0.145
70	0.041	0.073	0.100	0.122	0.140
80	0.040	0.071	0.097	0.118	0.137
90	0.039	0.070	0.095	0.116	0.133
100	0.038	0.068	0.093	0.113	0.131

The table shows, the power index of the current-voltage characteristic for the nonlinear limistor part β is higher than the power index of the surge arresters α. These indexes may have similar values $\beta = \alpha \approx 0{,}04...0{,}05$ only in a particular case.

With assigning base voltage

$$U_b = \eta \cdot u_m \,, \tag{7}$$

base values of resistance and current are determined as:

$$R_b = R_{lin}; \quad I_b = \frac{\eta \cdot u_m}{R_{lin}} \,. \tag{8}$$

Thus, (6) – (8) univalently determine the current-voltage characteristic of the nonlinear limistor part.

Resistance is generally determined as:

$$R = \rho \cdot \frac{l}{S} \,, \tag{9}$$

where

ρ – resistivity of a material, Ω·m;

l – resistor length, m;

S – cross-sectional area of the resistor, m^2.

Therefore, it follows from (2) – (3), that:

$$\rho_{nonlin}(\eta \cdot u_m) \frac{l}{S_{nonlin}} = \rho_{lin} \frac{l}{S_{lin}} \,, \tag{10}$$

and the ratio between the cross-sectional areas of the linear and nonlinear parts is determined as:

$$\frac{S_{lin}}{S_{nonlin}} = \frac{\rho_{lin}}{\rho_{nonlin}(\eta \cdot u_m)} \,, \tag{11}$$

i.e. the ratio between these cross-sectional areas depends on the ratio between resistivity of the materials. The resistivity of the nonlinear resistive material should be chosen for the voltage determined in (2).

The heterogeneous limistor consists of N (N≥1) linear and M (M≥1) nonlinear resistors connected in parallel (Fig. 3).

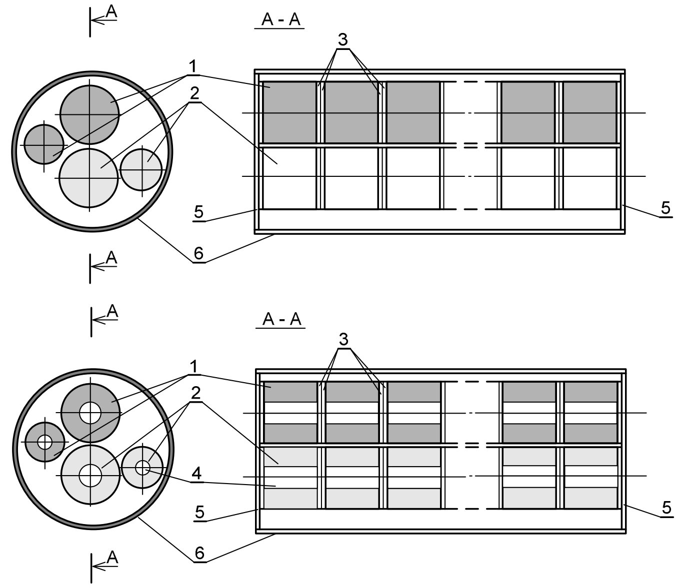

Fig. 3. Example of heterogeneous limistor, based on parallel connected N (N≥1) linear and M (M≥1) nonlinear resistors
1 – nonlinier resistors; 2 – linier resistors; 3 – metallized surfaces; 4 – axial holes ; 5 – electrodes ; 6 – fiber-glass reinforced plastic tube

Each resistor is assembled of discs made of ceramic [4] or other conductive materials [5] and placed on each other. In some cases, disks may have axial holes (like washer). The total resistance of the linear resistor is determined as:

$$R_{lin} = \frac{l}{\sum_{i=1}^{N} \frac{S_{lin,i}}{\rho_{lin,i}}} \,, \tag{12}$$

resistance of nonlinear resistors:

$$R_{nonlin} = \frac{l}{\sum_{i=1}^{M} \frac{S_{nonlin,i}}{\rho_{nonlin,i}}} \,. \tag{13}$$

In this case (11) is transformed in the following way:

$$\sum_{i=1}^{N} \frac{S_{lin,i}}{\rho_{lin,i}} = \sum_{i=1}^{M} \frac{S_{nonlin,i}}{\rho_{nonlin,i}(\eta \cdot u_m)} . \quad (14)$$

In the particular case, when all linear resistive discs or all nonlinear resistive discs are made of the same materials, (11) is transformed as follows:

$$\frac{\sum_{i=1}^{N} S_{lin,i}}{\sum_{i=1}^{M} S_{nonlin,i}} = \frac{\rho_{lin}}{\rho_{nonlin}(\eta \cdot u_m)} . \quad (15)$$

Assuming all discs to have the same diameter, linear and nonlinear resistors quantity should satisfy the following:

$$\frac{N}{M} = \frac{\rho_{lin}}{\rho_{nonlin}(\eta \cdot u_m)} . \quad (16)$$

Parameters of the material used for nonlinear resistors should comply with (6) – (8) in each case.

III. MODELING OF ELECTROMAGNETIC TRANSIENTS FOR POWER SYSTEM WITH LIMISTOR

A mathematical limistor model for electromagnetic transients calculation is based on the following equations:

$$u_{\lim} = R_{lin} \cdot i_{lin} ; \quad (17\text{-}1)$$

$$u_{\lim} = A \cdot i_{nonlin}^{\beta} ; \quad (17\text{-}2)$$

$$i_{\lim} = i_{lin} + i_{nonlin} , \quad (17\text{-}3)$$

where $A = U_b / I_b^{\beta}$.

Based on (17-1) – (17-3) the following equation is obtained for absolute values of voltage $\left(\left|u_{\lim}^{n+1}\right|\right)$ and current $\left(\left|i_{\lim}^{n+1}\right|\right)$ of a limistor in (n + 1) time step of calculation:

$$F(\left|u_{\lim}^{n+1}\right|, \left|i_{\lim}^{n+1}\right|) = \left(\frac{\left|u_{\lim}^{n+1}\right|}{A}\right)^{1/\beta} + \frac{\left|u_{\lim}^{n+1}\right|}{R_{lin}} - \left|i_{\lim}^{n+1}\right| = 0 . \quad (18)$$

Using Newton-Raphson linearization:

$$\frac{\partial F}{\partial \left|u_{\lim}^{n+1}\right|}\left(\left|u_{\lim(s)}^{n+1}\right|, \left|i_{\lim(s)}^{n+1}\right|\right) \cdot \left(\left|u_{\lim(s+1)}^{n+1}\right| - \left|u_{\lim(s)}^{n+1}\right|\right) +$$

$$+ \frac{\partial F}{\partial \left|i_{\lim}^{n+1}\right|}\left(\left|u_{\lim(s)}^{n+1}\right|, \left|i_{\lim(s)}^{n+1}\right|\right) \cdot \left(\left|i_{\lim(s+1)}^{n+1}\right| - \left|i_{\lim(s)}^{n+1}\right|\right) = -F\left(\left|u_{\lim(s)}^{n+1}\right|, \left|i_{\lim(s)}^{n+1}\right|\right),$$

final equation for a limistor is obtained:

$$\left[\frac{1}{A\beta}\left(\frac{\left|u_{\lim(s)}^{n+1}\right|}{A}\right)^{1/\beta - 1} + \frac{1}{R_{lin}}\right] \cdot u_{\lim(s+1)}^{n+1} - i_{\lim(s+1)}^{n+1} =$$

$$= sign(u_{\lim(s)}^{n+1}) \left(\frac{1}{\beta} - 1\right) \left(\frac{\left|u_{\lim(s)}^{n+1}\right|}{A}\right)^{1/\beta} , \quad (19)$$

which is solved iteratively (s – iteration number) with $u_{\lim(0)}^{n+1} = u_{\lim}^{n}$, $i_{\lim(0)}^{n+1} = i_{\lim}^{n}$.

Such model is implemented in MAES software (**M**odeling and **A**nalysis of **E**lectrical Power **S**ystems) [14]. All calculation results were obtained using this software for electromagnetic transients modeling.

IV. APPLICATION OF LIMISTOR

An example of the limistor application in the 500 kV system is reviewed below. An important practical objective is solved – breaking capacity of SF6 circuit breakers is provided when switching compensated power lines [6] – [13]. Connection of a resistor into a circuit of shunt reactors (Fig. 4) is usually applied, as it is an efficient method for damping the DC component of current through a circuit breaker [11]. It ensures fault-free operation of the circuit breaker.

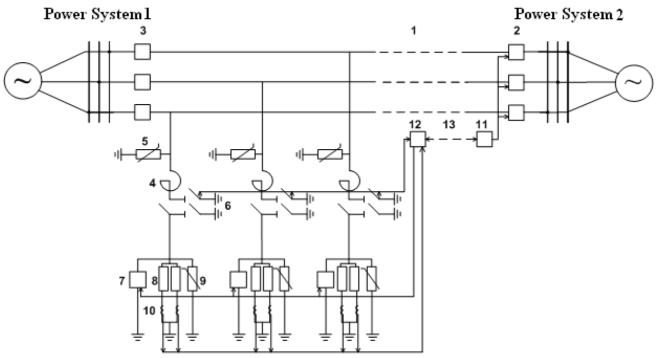

Fig. 4. Compensated transmission line with a resistor connected into the circuit of each shunt reactor

1 – transmission line; 2, 3 – 500 kV circuit breakers; 4 – shunt reactor; 5 – 500 kV surge arrester; 6 - break switch; 7 - 35 kV bypass circuit breaker; 8 – resistor (or limistor); 9 - 35 kV surge arrester; 10 – current transformer; 11 - relay protection unit; 12 – control unit; 13 - telecommunication

The circuit breaker (7), which bypasses the resistor (8), is closed under normal operating conditions of the transmission line (1). At short circuit occurrence, the relay protection system (11) issues a command for two-sided tripping of the transmission line. At the same time, a command is generated for circuit breaker (7) opening, thereby current starts flowing through the resistor. In the case of successful two-sided reclosing (with DC component being damped), a command is generated for closing the circuit breaker (7). Normal operation of the shunt reactor is continued.

Resistance value of such resistor should be chosen in the way that the shunt reactor voltage would not exceed the maximum permitted voltage for the grounded side of the shunt reactor. The rated voltage for the grounded side of 500-750 kV shunt reactors is 35 kV, the maximum operating voltage is 40.5 kV, the one-minute testing voltage is 85 kV.

Operation of the shunt reactor involves temporary connection (<1min) of the resistor into its circuit. In this case, resistance R_{res} of this resistor under steady-state conditions is determined as follows (neglecting shunt reactor resistance):

$$R_{res} \le \frac{X_{reac}}{\sqrt{\left(\left(U_{s,mo}/\sqrt{3}\right)/\left(k_{tot} \cdot U_{\mathrm{N(1)}}\right)\right)^2 - 1}},$$

where $U_{s,mo}$=525 kV – maximum operating voltage of the system; $U_{N(1)}$ = 85 kV – one-minute testing voltage for the grounded side of the shunt reactor; $k_{\mathrm{tot}} \approx 0.7$ – total factor which takes insulation co-ordination factor and safety factor into account.

Resistance of the resistor is:

$$R_{res} \le \frac{X_{raac}}{\sqrt{(303/60)^2 - 1}} = 0{,}2 \cdot X_{reac},$$

and $R_{\mathrm{res}} \le 180\ \Omega$ with $X_{\mathrm{reac}}=917\ \Omega$.

However, first voltage peak reaches 127 kV (Fig. 5) at the resistor with R_{res}=180 Ω (at the grounded side of the shunt reactor) because of the transient current flowing in the circuit. Such voltage is not permitted, as $127>85 \cdot 0.7 \cdot \sqrt{2}$ =84 kV. That is why resistance of the resistor should be decreased or some other measures should be taken. But resistance decreasing is often impossible, as it reduces the effect of the DC component damping.

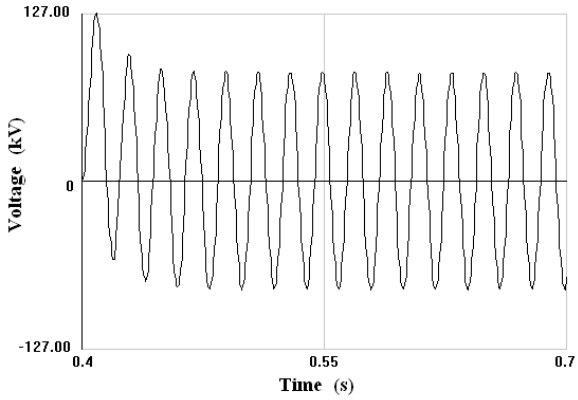

Fig. 5. Transient voltage at the grounded side of the shunt reactor with a linear resistor connected

Let us consider application of the limistor (U_b=84 kV, I_b=0.467 kA, β=0.176) instead of a linear resistor. The first transient voltage peak is limited to 80 kV (Fig. 6), such voltage is permitted. Then, limistor operation has no difference from the operation of a linear resistor.

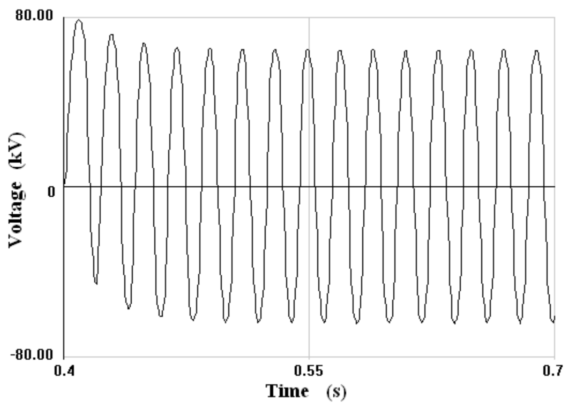

Fig. 6. Transient voltage at the grounded side of the shunt reactor with a limistor connected

The limistor may be connected in parallel with a surge arrester. In this case, their behavior is different. Resistance of the surge arrester (R_{arrest}), nonlinear part of the limistor (R_{nonlin}) and total resistance of the limistor (R_{lim}) versus voltage characteristics are shown in Fig. 7.

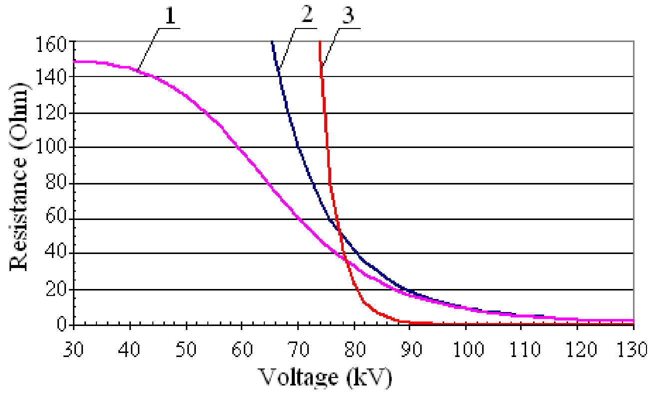

Fig. 7. Resistance of the limistor and surge arrester versus voltage characteristics (1 – Rlim, 2 – Rnonlin, 3 – Rarrest)

Resistance of the limistor virtually does not change and equals its linear part resistance up to 50 kV; resistance of the nonlinear part of the limistor and resistance of the surge arrester are very high. Resistance of the limistor gradually decreases within the range of 50 – 78 kV, resistance of the surge arrester is decreasing sharply. At 78 kV, resistance of the limistor becomes equal to the surge arrester resistance. Then, these two resistances decrease, but the surge arrester value becomes lower. After 90 kV, resistance of the surge arrester is significantly lower than the resistance of the limistor. Thus, voltage ranges of limistor operation (up to maximum operating voltage) and surge arrester operation (switching and lightning overvoltage) are separated. It should be noted, that frequency ranges of limistor and surge arrester operation are also separated: limistor is operated at a power frequency voltage, surge arrester is operated at higher frequency (in particular, frequency of switching and lightning overvoltage).

V. Conclusions

1. New nonlinear element of a network is described – limiting resistor (limistor). Heterogeneous design of the limistor is the most reasonable from the point of the manufacturing technique. In this case, the linear and nonlinear parallel parts of the limistor are formed from separate resistors.
2. To provide the required parameters of the limistor, certain requirements on the used constructional elements and electrophysical parameters of materials should be fulfilled.
3. The described example of limistor application shows that limistors are needed in power engineering.

VI. References

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