AC Voltage Normalization – Conception and Technology for Smart Grid System

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***Abstract*— The paper presents research aimed at determining the impact of innovative technology on system properties and characteristics of distribution electric system, including the tasks going beyond voltage regulation in set modes. Experimental research has been carried out on a physical model of electric grid with determination of the impact of Normalizer of AC Voltage on static characteristics of load, transfer capacity of the grid, stalling of asynchronic motors.**

Index Terms--**Technological Innovation, Power Quality, Smart Grid System, Electric Grids, Power Systems Operations and Control, Load management, Regulators, Voltage control, Energy efficiency, Demand Side Management.**

I. Introduction

In the world practice a great lot of theoretically based and introduced methods are used which are directed at reaching optimal modes of energy transmission and consumption, primarily throiugh Voltage control.

The existing methods of voltage control are mainly directed at the optimization of energy transmission modes at the voltage level higher than 0.4 kV. The main criterion at that is the minimum of losses at transmitting electric energy, which is achieved, among others, by increasing voltage in all supply networks.

The practice shows that at low voltage level (0.4 kV) up to 70% of electric energy is consumed, whereas at high voltage levels - 30%, and the correlation between the values of losses is, correspondingly, 85% and 15%. It is also known, that large municipal entities consume up to 70% of electric energy, and, accordingly, 30 % are consumes in the countryside. At that, 70% of consumers at the level of 0.4 kV get increased voltage, and 30% - reduced voltage, as the majority of large nods of city loads, characterized by concentrated electric grids of 0.4 kV, are under increased voltage, whereas in the countryside, the voltage is reduced due to losses in extended electric grids with low transmission capacity.

There exists quite an understandable antagonism between the stages of transmission and consumption of electric energy [2]. From the point of view of transmission networks, the higher the voltage in high voltage lines, the lower losses during transmission, that is why, especially in cities, the voltage 10.6 kV and 6.4 kV often comes on the high voltage side at transforming substation of 10/0.4 kV and 6/0.4 kV accordingly, which results in a considerable increase of voltage at consumers at the level of 0.4 kV, and, consequently, in an unjustifiable overconsumption of electric energy, significant current overloads in electric rids with the voltage 0.4 kV, decrease of service life of the equipment and the growth of its accident rate.

In other words, it is really rather difficult to meet the standards for the energy quality existing in the world, for example, the standard EN 50160 [1], in which voltage is the most important parameter and takes the first place in significance. It all means that any consumer of energy who gets energy supply in the frameworks of the Standard must work in the normal operation mode, i.e., their consumer parameters must correspond to the standard. In this case, the most favorable mode of energy supply is the mode corresponding to the lower voltage level, allowed by the Standard. It results in economic effect, both as a consequence of reducing the consumption of electrical capacity and energy, and a considerable increase of operational life of electrical equipment, that is, increase of life service and reduction of operating costs due to part load mode of energy supply on voltage.

Of course, there exists a possibility to solve, to a certain extent, the task of voltage control at the level of 0.4 kV by switching taps of supply transformers, however, this measure does not possess sufficient selectivity, thus, when supplying consumers at a significant distance from a step down transformer, it can lead to some inadmissible drop of voltage caused by losses in supply networks. Furthermore, such taps have episodic, seasonal, as a rule, character and are not welcomed by the operating staff.

The offered solution to the task is based on voltage control in the immediate proximity to the consumer by means of the system of normalizing ac voltage by using innovative patented devices of *Demand Side Management* [3, 4, 5, 6, 7, 8, 9, 10, 11,12, 13, 14, 15], called by the authors "normalizers of ac voltage" (NV) which provide voltage control in the range favorable for electric consumers.

The core consists in a method according to which the voltage of loading is regulated not by a power part of a network, but by electromagnetic connection of winding of volto-additional transformer with the currents which are 15-20 times lower than power current. The capacitance of the regulated device is not more than 5% of the loading capacitance.

At present, Normalizers of AC Voltage, realizing automatic discrete regulation of supply voltage, with the aim of achieveing its lowest level, admissible by standards on electric energy, have been introduced into thousands of enterprises in the world, and their above-mentioned efficiency has been convincingly proved.

II. Conception and Technology for Smart Grid System

As the introduction practice shows, though the normalizer of ac voltage is developed specially as local equipment for voltage control at consumer connections in the favorable zone, in practice it is included in the existing system of voltage control and becomes an active element of Smart Grid System [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

The carried research shows that with the mass introduction of the patented innovative method and device of "normalizer of ac voltage" (NV) into Smart Electric Grids the largest effect, connected with the increase in energy efficiency of the energy system, can be achieved if the electric power is transferred to the customer by the energy-supplying organization at the maximum value of voltage permitted by International Standard for the norms of power quality [1], and the customer uses it at the minimum voltage value, permitted by these Standards. On the one hand, such regulation allows to provide normal functioning of customers, on the other hand, the consumers will not use "extra" capacity, and the losses will be minimal. Therefore, one of the tasks of reducing the consumption of electric energy and the increase in energy efficiency of energy systems consists in regulating consumers' voltage. This task is typical of most countries of the world

The further development of the application of Normalizers of AC Voltage in electric grids is connected with the expansion of spheres of their use and requires answers to some questions.

1. In the course of research there were set tasks of finding other effects from using Normalizers of AC Voltage, namely: is it possible to increase the transfer capacity of the grid, the stability of motive load, etc.?
2. Is there any negative influence of voltage normalizing on power bus of consumers, on transfer capacity of the grid and its other properties and static characteristics of loads?
3. In what points of the grid does the use of Normalizers of AC Voltage provide their maximum efficiency in application to different purposes?

In order to answer these questions, analytical and experimental researches on a physical model of electric grid have been carried out, which allowed to make conclusions concerning additional positive effects of devices NV, used before only for normalizing voltage on power buses of consumers, namely:

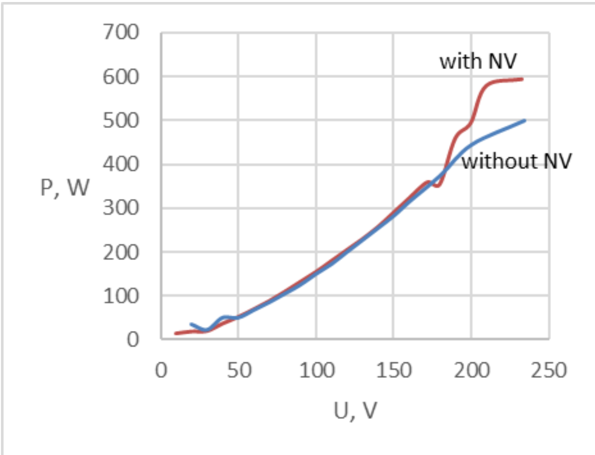
- the increase of limits of output capacity of electric generators, included into electric grid;
- the increase of stability of the work of asynchronic motors in the electric grid;
- the increase of transfer capacity of electric grid.

The obtained characteristics and oscillorgams of the processes permit to estimate the potential of the use of devices NV as an element of the system of managing the mode of distribution electric grids.

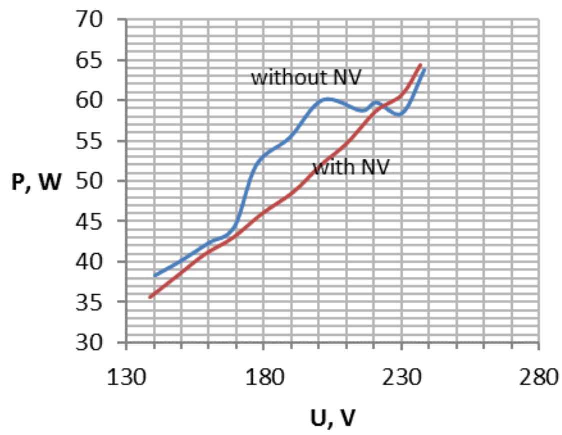
III. Analytical and Experimental Research of the Use of Normalizer Of AC Voltage (NV)

A. The impact of Normalizer of AC Voltage on Static Characteristics of Load

Experimental static characteristics of lighting and motive (asynchronic motor) loads are presented in Fig.1.



a) Lighting load



b) Motive load

Fig. 1. Static characteristics of load with normalizer of ac voltage and without normalizer of ac voltage.

From the presented diagrams it is seen that the use of Normalizer of AC Voltage (NV) considerably heightens the steepness of static characteristics of lighting load and reduces that of motive load.

B. The impact of Normalizer of AC Voltage on the limit of transferred capacity by conditions of stable transfer from the generator through the power line into the system with its direct-axis switch.

With the purpose of analytical determination of the character and degree of influence of Normalizer of AC Voltage we will present the following equivalent circuit of the power line (Fig. 2).

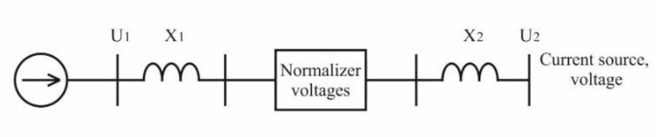


Fig. 2 Analog equivalent circuit of power transmission for researching the limit of transferred capacity with direct-axis switched Normalizer of AC Voltage

We take the coefficient of tranformation of NV for the modes of volt-restriction, transit and bootstrap as equal $K_T = 0{,}9;\ 1;\ 1{,}1$.

We will reduce the parameters of power transmission to the nominal voltage U_1 (1, 2):

$$X_2' = X_2 * K_T^2, \quad (1)$$

$$U_2' = U_2 * K_T \quad (2)$$

The expected value of the maximum limit of the transferred capacity by conditions of stability is determined according to the formula (3).

$$P_{max} = \frac{U_1 * U_2'}{X_1 + X_2'} = \frac{K_T * U_1 * U_2}{X_1 + K_T^2 * X_2} \quad (3)$$

By switching NV from the side of the source U_1 we take $X_1 = 0$, $X_2 = 2X$, and with switching from the source U_2 correspondingly $X_1 = 2X$, $X_2 = 0$, and with switching NV in the middle point of the power line $X_1 = X_2 = X$.

For the analysis we assume: $U_1 = U_2 = 1$ и $X = X_1 = X_2 = 1$.

With power transmission in the mode of transit or without NV the limit of transferred capacity is determined by the expression (4).

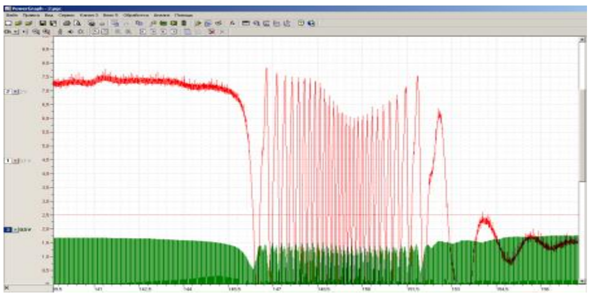
$$P^*_{max} = \frac{U_1 * U_2}{X_1 + X_2} = 0{,}5 \quad (4)$$

We will tabulate the calculation results P_{max} for different values of the transformation coefficient K_T and the place of location of Normalizer of AC Voltage in power transformation (Table I.)

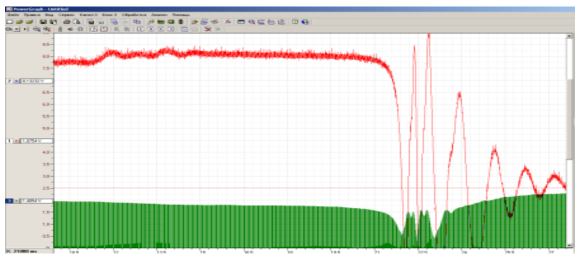
TABLE I
THE IMPACT OF NORMALIZER OF AC VOLTAGE ON THE LIMIT OF TRANSFERRED CAPACITY BY CONDITIONS OF STABILITY

		Place of location and correlation of parameters of Normalizer of AC Voltage		
		$X_1 = 0$, $X_2 = 2X$	$X_1 = X_2$	$X_1 = 2X$, $X_2 = 0$
P_{max}		$\frac{1}{2 * K_T}$	$\frac{K_T}{1 * K_T^2}$	$\frac{K_T}{2}$
K_T	0,9	$1{,}11 * P^*_{max} = 0{,}555$ Increases by 11%	$0{,}994 * P^*_{max} = 0{,}497$ Does not influence	$0{,}9 * P^*_{max} = 0{,}45$ Reduces by 10%
	1	Does not influence	Does not influence	Does not influence
	1,1	$0{,}908 * P^*_{max} = 0{,}454$ Reduces by 9,2%	$0{,}995 * P^*_{max} = 0{,}498$ Does not influence	$1{,}1 * P^*_{max} = 5{,}5$ Increases by 10%

By the results of modeling on electro-dynamic model of such an electric grid, the oscillograms of voltage and the limit of transferred capacity of electric power on the line with NV and without NV were obtained (Fig. 3). The modelled circuit corresponds to the conditions when NV is located near the source U_2 и $X_1=2X$, $X_2=0$.



a) without Normalizer of AC Voltage



b) with Normalizer of AC Voltage

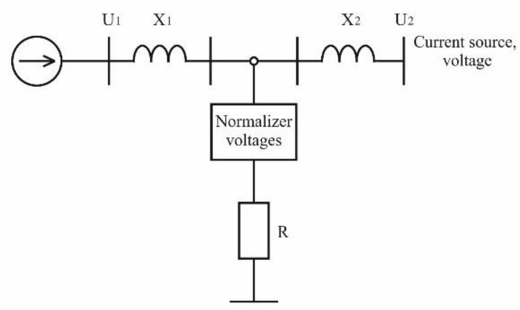
Fig. 3. Oscillograms of the experiment on determining the limit of the capacity transferred along the line and voltage on buses: a) without Normalizer of AC Voltage, B) With Normalizer of AC Voltage.

The limit of transferred capacity increased in the circuit with Normalizer of AC Voltage by 10%, which confirms analytical calculations.

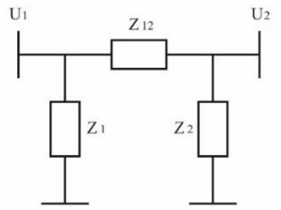
From the obtained results it follows that with the direct-axis switch of NV for regulating the limit of transferred capacity of power transmission it should be switched nearby consumers, and according to regulation tasks it is necessary to set the required transformation coefficient of Normalizer of AC Voltage.

C. The impact of Normalizer of AC Voltage on the limit of transferred capacity with the cross-sectional switch of NV into power transmission and load operation.

The equivalent circuit of power transmission is presented in Fig. 4.



a)



b)

Fig. 4. Equivalent circuits of substitution of power transmission for researching the limit of transmitted power with cross-sectional switch of Normalizer of AC Voltage: a) original, b) after the transformation of the star into the triangle.

Let us modify the circuit of Fig. 4 into calculation circuit (Fig. 5) and present the power $P_{1\Sigma}$ provided by the source U_1 through components (5):

$$P_{1\Sigma} = P_1 + P_{12} \tag{5}$$

where P_1 – power provided for load R, P_{12} – interchange power.

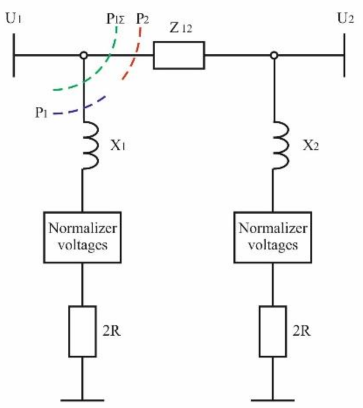


Fig. 5. Transformed calculation circuit of the substitution of power transmission for research of the limit of transmitted power with cross-sectional switch of Normalizer of AC Voltage

In the result of transformations of the circuit in Fig. 5 we obtain the values of resistance (6), (7).

We assume: $U_1 = U_2 = 1$, $X = X_1 = X_2 = R = 1$.

Then:

$$\dot{Z}_1 = \dot{Z}_2 = 2RK_T^2 + jX = 2K_T^2 + j, \tag{6}$$

$$\dot{Z}_{12} = jX_1 + jX_2 - \frac{X_1 X_2}{RK_T^2} = -\frac{1}{K_T^2} + 2j \tag{7}$$

The power P_1 is determined according to the expression (8):

$$P_1 = I_1^2 2RK_T^2 = \frac{U_1^2}{X_2 + (2RK_T^2)^2} * 2RK_T^2 = \frac{1}{\frac{1}{2K_T^2} + 2K_T^2} \tag{8}$$

The power P_{12} is power-angle curve of power transmission depending on resistance Z_{12} and determined by the expression (9):

$$P_{12} = \frac{U_1^2}{Z_{12}} \sin\alpha_{12} + \frac{U_1 U_2}{Z_{12}} \sin(\delta - \alpha_{12}) \tag{9}$$

где $\alpha_{12} = \mathrm{arctg}(\frac{R_{12}}{X_{12}})$

Maximum value of P_{12} will be obtained under the condition $\delta = \alpha_{12}$ through the following (10):

$$P_{12}^{max} = \frac{U_1^2}{Z_{12}} \sin\alpha_{12} + \frac{U_1 U_2}{Z_{12}} = \frac{1}{\sqrt{\frac{1}{K_T^4} + 4}} \left(\sin\left(\mathrm{arctg}\left(\frac{1}{2K_T^2}\right)\right) + 1\right) \tag{10}$$

The calculations of parameters of equivalent circuit of power transmission in Fig. 5 in different modes of operation of NV are presented in the table (Table II).

TABLE II

DEPENDENCE OF PARAMETERS OF EQUIVALENT CIRCUIT OF POWER TRANSMISSION ON THE OPERATIONAL MODE WITH CROSS-SECTIONAL SWITCH OF NORMALIZER OF AC VOLTAGE

№	Параметр	$K_T = 0{,}9$	$K_T = 1$	$K_T = 1{,}1$
1	$\dot{Z}_1 = \dot{Z}_2$	1,62+1j	2+1j	2,42+1j
2	$\dot{Z}_{12}$	-1,23+2j	-1+2j	-0,83+2j
3	P_1	0,446	0,4	0,353
4	P_{12}^{max}	0,648	0,646	0,653
5	$P_{1\Sigma}^{max}$	1,094	1,046	1,006

From the results it follows that Normalizer of AC Voltage makes a considerable impact on the value of power capacity P_1 from the source on load within the limits of 23%. The impact of Normalizer of AC Voltage on the limit of interchange power P_2^{max} is of no consequence (approximately 1,1%.) The impact of Normalizer of AC Voltage on the maximum of output capacity $P_{1\Sigma}^{max}$ is considerable and amounts to 8,4%.

D. The impact of Normalizer of AC Voltage on dynamic stability of motive load

From the analysis of experimenatl oscillograms one can make the conclusion that with regular response time of operation steps, Normalizer of AC Voltage does not influence the stability of motive load, as the input of the bootsrtap step of NV is delayed. The positive influence appears with the reduction of delays in operation of bootstrap steps.

Conclusion

As a result of research, there was proved, analytically and experimentally, the posibility and practicability of the multi-purpose use of Normalizer of AC Voltage in distribution electric grids.

The obtained characteristics and oscillograms of the processes allow to estimate the potential of the use of Normalizer of AC Voltage as an element of the system of managing the mode of distribution electric grids.

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