SIMPLE AND EFFICIENT SOLUTION FOR REHABILITATION OF CONDITIONS FOR VOLTAGE REGULATIONS IN DISTRIBUTION NETWORK

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INTRODUCTION

In modern society, life without electricity is inconceivable. Electricity, which is produced in power plants is transmitted over a high voltage network to a greater or lesser distance. The distribution network directs it through a series of distribution transformers through medium and low voltage grids to consumers. Electrical energy total price paid by the consumers must meet the appropriate power quality per standards (*EN 50160*), while on the other hand the electrical distributor must consider the economic parameters and profitability of the investment. Distribution of electricity in newly built, dense (urban settlements) consumer areas is not a problem in terms of the quality of electricity supplied and the cost-effectiveness of the capital investment project. Distribution of electricity in sparse and small (rural settlements) consumer areas, as well as areas with older electrical infrastructure can experience a quality of delivered electricity which is below the standard EN 50160. This creates a problem in the cost-effectiveness of the capital investment, creating utility losses and system inefficiencies (so-called useless power facility) and as such creates dissatisfaction among consumers. Typically, the most distant consumers from the corresponding substation are subject to the poorest quality of the delivered electricity. This paper presents a new system, a self-regulating energy regulator "*VROT-18 system*", which is intended to manage voltage conditions in low voltage networks, achieve load balancing along the lines where it is installed, eliminate return current through a neutral conductor for consumers connected behind the " *VROT-18 system*" device, to improve the operating conditions of the grid protection system, as well as the selectivity of the protection. It is also intended to protect consumers from excessive voltage when short circuits occur between the phase and neutral conductor. It is especially important to emphasize its capability for transmitting high to maximum nominal power through low voltage lines.

COMPARISON BETWEEN CLASSIC METHODS AND THE NEW METHOD FOR RESOLVING VOLTAGE PROBLEMS IN THE DISTRIBUTION NETWORK

The classic methods used to resolve the quality of electricity supply in the existing electricity, infrastructure are:

a.) Increasing the voltage at the associated 10 / 0.42 kV transformer substation to a level of 253V. This is an inefficient solution since the end consumers do not receive a satisfactory voltage level and is also harmful because at the lowest unbalanced loads, there is an increase in voltage above 253V in the underloaded phases and depending on the amount of total unbalanced lads, this voltage can surpass 260V for a duration more than 500ms. This method does not address the reduction of harmonic distortions, nor the selectivity and sensitivity of the protection response. The investment is low, but inefficient.

b.) Increasing the cross-section of conductors, by installing conductors with larger cross-section or by installing parallel conductors, is a more efficient solution than the solution mentioned under point a.). However, with the installation of additional conductors on poles, the pole location becomes incrementally loaded, and in unbalanced load regimes, depending on the cross section of the conductors and the length of the low-voltage lines, does not achieve a satisfactory voltage level for the most distant consumers, nor does it solve the problem of selectivity and sensitivity of protection response, nor reduced harmonic distortion. The investment cost is high and limited in terms of providing adequate voltage levels to end consumers, and inefficient in terms of selectivity and sensitivity of protection response and reduction of harmonic distortions.

c.) Increasing the cross-section of conductors and installing capacitor batteries is an expensive method, and there is a possibility of voltage increase above 260V for duration of more than 500ms, as well as a significant increase in harmonic distortions, which does not allow selectivity of protection response.

d.) Construction of medium voltage power lines with associated transformer substation 10 (20) /0.42, 50 kVA, is an effective method, but investment cost is very high, especially if there is only a small group of consumers at the end of an existing low voltage power line.

The new method "*VROT-18 system*" with the associated device has the same efficiency as a 10 / 0.42 kV transformer substation, using power from the existing low-voltage power line. The operating system is not based on voltage rise but on balancing load, and with its suitable coupling enables elimination of harmonic distortions generated by consumers on the section of low voltage line supplied by the "*VROT-18 system*". In addition, it enables an increase of selectivity and sensitivity of the protection response.

There are many advantages in using the "*VROT¬18 system*", including:

- easy and fast installation;
- small investment cost when reconstructing the network;
- significantly higher system efficiency in energy transmission along the low voltage line;
- reduced energy losses during distribution to consumers;
- the possibility of transferring significantly higher power over longer distances while maintaining continuous voltage conditions along the low voltage line within the limits defined by the standards and *EN 50160*;
- eliminated the influence of higher harmonics due to galvanic isolation;
- eliminated load in the neutral conductor to the substation, in case of large, unbalanced loads, because $I_0 = 0$ at the installation site;
- increased protection of consumers from excessive voltage in case of short circuit of phase and neutral conductor or interruption of the neutral conductor;
- load balancing within phase conductors;
- achieved selectivity and sensitivity of protection action along the low voltage line;
- in combination with a self-supporting cable bundle does not require maintenance of that outlet from the transformer substation, especially if the power line passes through areas with tall dense vegetation;
- very suitable as a replacement for TS 10 / 0.4 kV, up to 50 kVA when supplying a small number of consumers;
- if used as a replacement for TS 10 / 0.4 kV, up to 50 kVA, the number of outages in the main 10 (20) kV high voltage lines passing through areas with tall and dense vegetation that supply small power substation TS 10 / 0.4 kV will be reduced;
- it is very suitable for ring concept network design from TS 10 / 0.4 kV 250 kVA with 5 outlets of 50 kVA each;

- is very suitable for use in industrial facilities, large buildings, remote consumers, and shopping malls for a distributed power supply system.

INTRODUCTION OF "*VROT-18 SYSTEM*" IN THE DISTRIBUTION NETWORK

Voltage is the basic and main parameter of an electrical power system, on the basis to which all the remaining parameters that define the technical performance of the power systems, are formed. When distributing electrical power, it is very important to maintain satisfactory voltage levels along the distribution paths. If we transmit electrical power along a low-voltage power line, in addition to characteristics (like active, inductive, capacitive), the load mode (balanced, unbalanced) becomes very important. The character and load regime that prevail on the low-voltage power line during the distribution of electric power significantly affects the change of voltage, which affects the quality, quantity, and time for the delivery of transmitted electric power / energy.

When we design and build distribution lines for the electrical power with specific technical characteristics, i.e., only for active and balanced loads, and if there is a change in the character or load regime, the designed and built distribution lines will not satisfy its purpose. On the other hand, if the distribution grids were designed and built according to the criterion of the most unfavorable condition, i.e., for inductive and only unbalanced loads, investments would be too large and become unprofitable. For designing and building the distribution grids to have profitable and efficient investment, it is necessary to design and build distribution grids according to the criteria of active and balanced loads. By installing automatic regulators along the length of the distribution lines, it will eliminate the occurrence of the most unfavorable conditions which usually happen at the end of those lines.

The automatic voltage regulator "*VROT-18 system*" is a device of uncoupled type that independently controls the character and load regime per phase and uses line voltage for control. It is installed in the low-voltage electricity distribution network to enable voltage stability by eliminating the influence of specific unfavorable characters and load regimes to efficiently supply electricity. The efficiency of electricity supply is reflected in quality and continuity defined within the standard *EN 50160*, with reduction of technical losses of electrical power in the distribution lines, significantly lower loss of leaked energy, increased transmission of maximum power along low voltage lines, significantly better network intermittency, selectivity, and responsiveness protection. In addition to efficiency in electricity supply by "*VROT-18 system*" when compared to conventional methods of improving power transmission (construction of medium voltage line with a transformer substation) it requires a much smaller investment with a short implementation time, does not require maintenance, and is built entirely as dry technology (without oil) so that it is environmentally friendly, safe and applicable in all living (forest-weekend cabins, rural, suburban, and urban) environments.

Figure 1 shows the picture of the "*VROT-18 system*" device.

Figure 1. Picture of the "*VROT-18 system*" device

The basic elements of the "*VROT¬18 system*" are a **fuse box**, a special galvanically isolated **dry-type power transformer** and a **control box**.

The fuse box is equipped with an automatic high-power circuit breaker. The cover is transparent so that the status of the circuit breaker and protection element can easily be seen.

Dry power transformer is a special type of controllable transformer whose operation is based on the principle of controlling the variable structure of the galvanically separated circuit and does not belong to the group of autotransformers. It is made of the highest quality epoxy resins intended for outdoor and indoor installation, and the dimensions are optimized in regard to its power and location of installation. Special attention is paid to the design, mechanical and electrical characteristics in terms of thermo-dynamic, dielectric loads, losses (losses in iron and copper), which makes this device very efficient, reliable and attractive.

The control box is made of the highest quality PVC materials complying to IP 54 protection and is equipped with electronics that are galvanically separated from the low voltage network. Specially designed electronics give an automatic instruction to the transformer to enter into the power regulation cycle. The electronic circuit also has a test-only function.

The working principle is based on the electronics that are galvanically separated from the low-voltage network, which monitors the state of the low-voltage line parameters at the installation site and performs control according to the written program. By installing the device at the designed point within the low voltage outlet line, exact and real time parameters are obtained at that installation site, identical to ones on the busbars of the associated transformer substation 10 (20) /0.4kV, so that the method of emulating the transformer substation TS 10 (20) /0.4kV at the installation point of the device is achieved.

The basic characteristics and their values of the "*VROT-18 system*" are shown in Table 1.

Table 1. Basic characteristics and their values of the "*VROT-18 system*"

Characteristics	**Value**
Nominal grid voltage [V]	420(438)/243(253)
Voltage value on outlet [V]	230 ± 10%
Nominal power [kVA]	18
Highest voltage [kV]	1
Test voltage 50Hz, 1 min [kV]	3
Lighting impulse voltage 1.2/50µs [kV]	5
Nominal current [A]	78
No load losses in transformer Pcun [W]/Pfe[W]	500/80
Transformer power factor cos ϕ	0.97
Mechanical protection	IP 54
Temperature range	from -40° C to 60° C
Installation	Any position on pole (or pad mounted)

The cost-effective investment and technically stable (0.95 degree of symmetry for cos ϕ = 0.95) designed and built electrical distribution network is a ring arrangement with equal radius, and the distribution feeders (conductors-cables) are sized according to the maximum simultaneous nominal electric power demand. Such a network, when initially designed, do not have "gray zones", i.e., areas where deviations of electrical parameters deviate from the standard *EN 50160* (outside of *EN 50160*), and the system is still efficient in terms of electricity supply to customers. Over time, there can be an increase in consumption (growing demand for more power), as well as a significant increase in unbalanced load (percentage of balanced load less than 75% to totally unbalanced load) because of many single-phase high-power consumers that cannot be balanced in the system by classical phase balancing methods. There is also an increase in harmonic distortion due to the presence of consumers with semiconductor (electronic) control components. All this leads to the creation of a "gray zone" (area outside *EN 50160*), which increases and expands by an average of 0.753% per year. The appearance of the "gray zone" mostly affects the electricity customers who are furthest away from the transformer substation. These customers become dissatisfied with the quality of the purchased energy since the purchased energy from the source substation does not enable their connected appliance to function properly and could cause damage and destroy the connected appliance. The distribution network becomes inefficient due to latencies and unstable, i.e., there is the occurrence of large voltage dips, due to increased unbalance and poor intermittence. Poor intermittence / latency is due to poor voltage and a large number of single-phase consumers demanding energy at the same time, resulting in longer times that currents are flowing through the phase and neutral conductors of low voltage lines and that creates energy losses in the distribution line defined by the following relations:

$$P_v\,[W] = r_v\,[\Omega/km] \cdot I_v^{2}\,[A] \qquad (1)$$

and the lost energy is:

$$W\,[kW/h] = P_v\,[W] \cdot t\,[h]\,/1000 \qquad (2)$$

In addition to the lost energy in the distribution feeder line, there is a loss in the undelivered energy, which directly affects the intermittence in the low voltage line. Undelivered energy is energy that could have been delivered to the customer but was not delivered due to poor voltage. The undelivered energy loss is calculated according to the following relation:

$$W_{lkd}\,[kWh] = W_n\,[kWh] \cdot K^2 \qquad (3)$$

where $K = U_{msr}\,[V] \,/\, U_n\,[V]$

Percentual energy loss due to inefficient electrical distribution network is calculated as follows:

$$G_{Wg}\,[\%] = (1- K^2)\cdot 100\% \qquad (4)$$

The following notations were used in the above expressions:
W_n [kWh] - energy delivered to the consumer under the nominal parameters of the network;
W_{lkd} [kWh] - energy delivered to the consumer in the "gray zone";
G_{Wg} [%] - percentual energy loss due to inefficient electricity distribution network;
U_{msr} [V] - measured voltage in the "gray zone" and
U_n [V] – grid rated / nominal voltage of 230V.

APPLICATION OF "VROT¬18 SYSTEM" IN THE DISTRIBUTION NETWORK

A self-regulating energy regulator "*VROT-18 system*" is constructed on a specially designed stainless-steel console. It is installed at a height of one meter below the lowest conductor of the low voltage network. Connection to low voltage network is achieved by connecting the primary conductors to the line voltage, and the secondary connects to phase and neutral conductor. A combined grounding must be done at the installation site. Use one transformer per phase. Figure 2 shows an example of the installation of the "*VROT-18 system*", while Figure 3 shows "*VROT-18 system*" installed as a replacement solution for Transformer substation 10 (20) /0.4 kV, 50 kVA

Figure 2.
"VROT-18 system" Installation example

Figure 3.
"VROT-18 system" as built example

Table 2 shows the voltage values in inefficient electricity distribution networks and the impact of reduced voltage levels on the loss of energy in "gray zones". In addition, this trend creates a poor intermittence, resulting in additional line losses in distribution. Power / energy loss on the distribution lines is defined by the following terms:

$$P_{vg}[W] = r_v[\Omega/km] \cdot I_v^2[A] \quad (5)$$

$$W_{vg}\,[kWh] = (P_{vg}[W] / 1000)\cdot t[h] \quad (6)$$

where the following designations were used:
I_v [A] - current in the distribution line;
r_v [Ω / km] - longitudinal resistance of the distribution line;
P_{vg} [W] - power loss in the distribution line;
W_{vg} [kWh] - energy loss on the distribution line, and
t [h] - time while P_{vg} [W] power last

Table 2. Voltage values in inefficient electrical distribution networks and the impact of reduced voltage levels on the energy losses in "gray zones"

U_{msr} [V]	**U_n [V]**	**$K = U_{msr}$ [V] / U_n [V]**	**W_{lkd} [kWh] = W_n [kWh] · K^2**	**G_{Wg} [%]**
230	230	1.00	W_{lkd} [kWh] = W_n [kWh]	0
207	230	0.90	W_{lkd} [kWh] = W_n [kWh] · 0.81	19.00
195	230	0.85	W_{lkd} [kWh] = W_n [kWh] · 0.72	27.75
190	230	0.83	W_{lkd} [kWh] = W_n [kWh] · 0.68	31.75
185	230	0.80	W_{lkd} [kWh] = W_n [kWh] · 0.65	35.30
180	230	0.78	W_{lkd} [kWh] = W_n [kWh] · 0.61	38.75
175	230	0.76	W_{lkd} [kWh] = W_n [kWh] · 0.57	42.10

Table 3 shows the influence of unbalanced load on the load lasting time, as well as energy loss within one hour.

Table 3. Influence of unbalanced load on the load lasting time and energy loss in one hour.

Method	Units	THREE PHASE USERS BALANCED LOADS					SINGLE PHASE USERS UNBALANCED LOADS				
		A	B	C	D	E	A	B	C	D	E
Nominal	P_n [kW]	7.0	10.0	25.0	25.0	10.0	1.0	3.0	5.0	10.0	5.0
	t_{ras}[h]	1	1	1	1	1	1	1	1	1	1
	W_{nd}[kWh]	7.0	10.0	25.0	25.0	10.0	1.0	3.0	5.0	10.0	5.0
With VROT18	P_{max} [kW]	7.0	9.39	21.6	29.6	8.42	0.98	2.72	4.10	9.13	4.47
	t_{nd}[min]	60	62.8	68.2	69.7	70.2	61.2	65.4	70.17	64.3	66.0
	W_{vg}[kWh]	9.73	0.32	0.3	0.1	0.005	2.32	$6x10^{-3}$	$1x10^{-3}$	$8x10^{-3}$	$3x10^{-3}$
Without VROT18	P_{max} [kW]	7.0	9.36	22.0	28.6	8.13	0.97	2.58	3.86	6.70	3.28
	t_{nd}[min]	60	63.1	67.1	72.1	72.6	61.8	69.7	77.7	89.5	91.46
	W_{vg}[kWh]	9.12	0.31	0.28	0.15	0.05	4.03	0.2	0.17	0.13	0.07

In Table 3, the following designations were used:
t_{ras} [h] - time required to engage rated power P_n [kW] to deliver W_{nd} [kWh] and
A, B, C, D, E - consumers connected to three-phase low voltage line.

Based on Table 3, it can be noticed that the required energy is distributed to customers in a shorter time using the "*VROT¬18 system*", which is especially pronounced in purely unbalanced network modes (many single-phase consumers demanding energy and connected to the same phase). The feature of efficient low-voltage electricity distribution networks is to achieve the shortest possible delivery time. According to Table 4, the impacts of power distribution through distribution lines are analyzed using the "*VROT¬18 system*" on three-phase low-voltage power lines, considering two end scenarios, when all connected consumers are three-phase and when all connected consumers are single-phase.

Table 4. Analysis of the impact on power distribution through distribution lines using the "*VROT¬18 system*" on a three-phase low-voltage power line considering two end scenarios, when all connected users are three-phase and when all connected users are single-phase

Units	THREE PHASE USERS BALANCED LOADS		SINGLE PHASE USERS UNBALANCED LOADS	
	With VROT	Without VROT	With VROT	Without VROT
P_n [kW]	87		24	
P_{max} [kW]	76.14	75.14	21.4	17.39
Δ P_{max} [kW]	76.14 - 75.14 = 1		21.4 - 17.39 = 4.01	
W_{nd}[kWh]	87		24	
t_{nd}[min]	70.2	72.6	70.17	91.46
W_{vg}[kWh]	10.45	9.91	2.41	4.60
Δ W_{vg} [kWh]	9.91 - 10.45 = -0.54		4.6 - 2.41 = 2.19	

Where is:
P_n [kW] -nominal simultaneous installed power;
P_{max} [kW] - maximum distributed power;
Δ P_{max} [kW] - difference in distributed power;
W_{nd} [kWh] - energy required from consumers;
Δ W_{vg} [kWh] - difference in energy losses;
W_{vg} [kWh] - energy loss in delivery W_{nd} [kWh], and
t_{nd} [min] - time required to deliver W_{nd} [kWh]

Based on the results in Table 4, it is concluded that at balanced load (only three-phase consumers connected to feeders) there is a slightly lower energy loss when the "*VROT¬18 system*" is not

integrated into the low voltage line, so under these operating conditions there is no need to install the "*VROT-18 system* "into the low voltage line (in accordance with *EN 50160*). However, if the degree of unbalanced load in the low voltage lines begins to grow, which is formed by single-phase consumers connected to the low voltage lines, then there are excessive voltage drops and a reduced supply of electricity (not in accordance with *EN 50160*), which leads to increased energy losses and in that case, it is necessary to make modifications to the low voltage lines.
To eliminate the problem of unbalanced loads and an unbalanced network in electricity distribution networks and to restore the network back to an efficient system, many methods have been proposed. The traditional methods used were: changing the cross section of conductors, or construction of medium voltage power lines with associated transformer substation, both of which require large capital investments, new equipment, technical resources and will take a long time to rebuild (about six months). By applying the "*VROT-18 system*", an efficient and effective system can be achieved with significantly smaller economical impacts and technical investments, and can be implemented in two hours.

CONCLUSION

In order to maintain an efficient electrical distribution system, it is necessary to solve the problems of "gray zones" which are usually formed at distances of 700m to 1200m from the associated transformer substation and consumer areas with installed power up to 50 kVA. Methods that successfully solve the problem of "gray zones" are the traditional construction of a medium voltage line with a new transformer substation and the application of new automatic voltage regulators "*VROT¬18 system*" installed along the length of the lines. Traditional methods require large capital investments and do not provide a significant Return on Investment (ROI).

By applying the new "*VROT¬18 system*" it is possible to achieve investment savings of 60% to 700% (depending on the reconstruction needs). This system significantly reduces the implementation time, requires a much smaller investment providing a much better ROI, and allows selectivity protection of medium voltage network to be effective in order to reduce the number of outages. The installation of "*VROT¬18 system*" in low-voltage power distribution lines that operates at the limits and below the limits of *EN 50160* in terms of voltage U_{min}[V] = 182, and also in power distribution lines where unbalanced load prevails, will increase overall electrical efficiency. The device "*VROT¬18 system*" is a new technological solution in distribution networks for the restoration of initial / original voltage conditions and has been proven in practice to be justified by doing a techno-economic analysis.

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