# PORTABLE REGULATOR: AN INDUSTRIAL SOLUTION FOR VOLTAGE REGULATION AT LV NETWORKS

Ricardo TUFANIUK
AES-Eletropaulo – Brazil
ricardo.tufaniuk@aes.com

Donorvan Rodrigo FAGUNDES
AES-Sul – Brazil
donorvan.fagundes@aes.com

Marcelo Aparecido PELEGRINI
SINAPSIS - Brazil
marcelo.pelegrini@sinapsisenergia.com

Juan Carlos CEBRIAN
SINAPSIS - Brazil
juan.cebrian@sinapsisenergia.com

Daniela Vinci KONDO
SINAPSIS - Brazil
daniela.kondo@sinapsisenergia.com

Francisco da Costa SARAIVA Filho
University of São Paulo - Brazil
saraiva@fei.edu.br

Silvio Xavier DUARTE
University of São Paulo - Brazil
xavier@pea.usp.br

Tiago Poles de SOUZA
University of São Paulo - Brazil
tiagopoles@pea.usp.br

## ABSTRACT

*This article focuses on the developing of a Portable Voltage Regulator for Low Voltage Networks (PVRLVN), for single phase, two phases and three phases networks, which envisages meeting the regulations, given that the time established by the regulatory standards is a factor that limits the planning and the execution of corrective actions. The first PVRLVN was developed inside a Research & Development Project financed by AES Eletropaulo, an energy distribution company with more than 5.8 million customers in the greatest city of Brazil. This PVRLVN, with 30 kVA nominal demand, 115V + 115V, 60 Hz and with the portability to be installed on a pole near customers with voltage problems, was developed, designed and tested in a laboratory and also in a real grid to be a temporary equipment that would adjust the voltage of the grid continuously to the right level until a definitive solution be done by the utility, avoiding penalties. The developed regulators were installed in several different locations in actual network of the AES Eletropaulo and AES Sul, both Brazilian local distribution companies.*

## INTRODUCTION

Currently, PRODIST (Procedures for Electric Energy Distribution), standard developed by ANEEL (Brazilian Electricity Regulatory Agency) [1], reaffirms as a consumer right to request measure of voltage delivered from the utility always any consumer to believe his voltage is not within the legally established limits. PRODIST also defines a periodic program of measurements, which a sample is drawn to calculate voltage indicators. Measurements should have duration of 168 hours and intervals of 10 minutes, totaling 1008 records. Measurements should be made between phases and between phases and neutral.
The doctrine of PRODIST about the compliance voltage is based on the comparison between the injury experienced by the customer due to incorrect voltage levels and the cost that the utility faces to reverse these critical voltage levels with improvement works. The PRODIST goal is not to become voltage ideal, but keeps it between a minimum and maximum relative to a reference value. The main challenge of ANEEL, to implement a regulatory approach, is the fact that associated injuries with poor voltage levels affect the client and, therefore, utilities are not motivated to invest in reducing this damage [2]. Thus, PRODIST imposes compensation in the bills of customers when the problems are not repaired in the deadlines set by PRODIST.
PRODIST sets limits for voltage steadied levels: "Adequate", "Precarious" and "Critical". These limits are used to define terms and compensation to consumers if the boundaries for adequate services are not reached. According to PRODIST to make the necessary corrections, the utility have a boundary of 30 days after diagnosis of consumer problem to prepare and execute a corrective work. Of course, depending on the corrective work complexity, this period is not enough, resulting in the payment of severance amounts.
This paper proposes to use electrical-electronic equipment for automatic voltage regulation in order to consider the voltage problem of consumers and insufficient time to carry out remedial works and to solve both problems. These devices were developed using as a base the prototype presented in [3] - [4], but some changes have been inserted in order to increase their functionality.

## DEVELOPED EQUIPMENT

The developed apparatus are two Portable Voltage Regulators for Low Voltage Networks (PVRLVN), which are designed to operate in low voltage networks. The first is three phases of 30 kVA - 220/380 V and the second is phase-phase 2-wire 10 kVA - 220 V. The main feature of these devices is the portability. They are designed to be fast and effective solutions, but temporary,

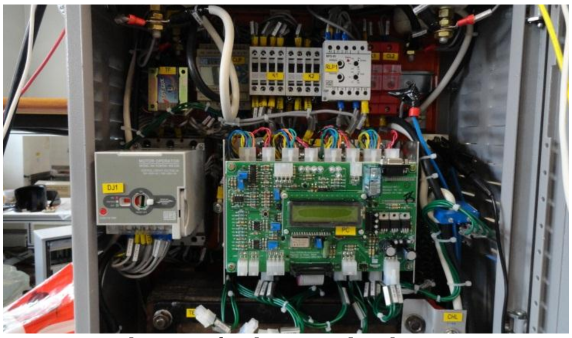

Fig. 1. Photo of the single-phase PVRLVN (internal).

Fig. 2. Photo of the single-phase PVRLVN (external).

to correct the voltage level of any consumer complainant. The PVRLVNs can be installed on a pole next to the consumer until a definitive solution is provided by utility. Some pictures of developed single phase PVRLVNs can be viewed on the Fig. 1 (internal) and Fig. 2 (external).

## Basic operation

The developed single-phase PVRLVN adjusts the unregulated voltage at its input terminals by adding or subtracting an appropriate amount of voltage. This is done through the secondary of a transformer "Buck-Boost" which is installed inside the PVRLVN. Hence, the connected load at its output terminals of PVRLVN receives a voltage within the established range by PRODIST [1]. On the other hand, the operation of three phase PVRLVN is done by phase, in other words, a transformer is used "Buck-Boost" for each phase.
The power control allows three basic actions in output voltage [4]:

1) To add voltage to its input voltage when it is below the lower limit set as an appropriate minimum;
2) To subtract voltage from its input voltage when it is above the upper limit set at most suitable;
3) To not add or subtract any voltage to the input when it is within the range established as appropriate.

In addition to controlling the polarity of the voltage in the transformer secondary "Buck-Boost", the controller controls the amount of voltage which is added or subtracted on the PVRLVN's output. There are six different levels of voltage regulating network:
i) supply voltage too low => To add a lot,
ii) supply voltage middle low => To add middle
iii) supply voltage low bit => To add a little
iv) supply voltage normal => To no add or subtract any amount,
v) supply voltage high bit => To subtracts a little
vi) supply voltage middle high => To subtract middle.

## Operation of Buck-Boost

The transformer "Buck-Boost" of PVRLVN serves to accomplish the task of adding and subtracting controlled amounts of voltage using three "taps" at its primary side. The control schematics and power boards of single-phase and three-phase PVRLVNs can be seen in Fig 3 and Fig 4 respectively.
The PVRLVN is designed to be connected to the secondary of the distribution transformer on any three-phase or single-phase distribution system. Each secondary winding of the "Buck-Boost" regulates individually each phase of the distribution transformer. The load receives the regulated voltage between phase and neutral. The keys S0, S1, S2 and S3 are composed of two SCRs in anti-parallel (AC_Switch) and its command is done through a driver board with pulse transformers in

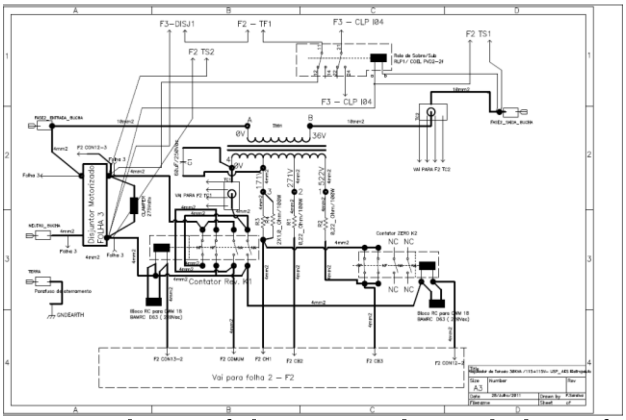


Fig 3 – Schemes of the power and control plates of Single Phase Voltage Regulator.

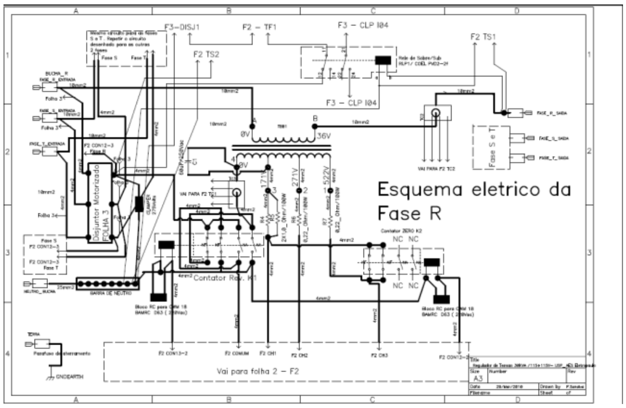


Fig 4 – Schemes of the power and control plates of Three Phase Voltage Regulator.

their gates.
The reverse polarity contactor (RPC) serves to reverse the polarity of the primary "Buck-Boost" in order to add or subtract voltage to adjust the voltage on the output to stay within the range required by PRODIST. The contact of zero relay (NF) is to ensure zero voltage in the Buck-Boost transformer secondary side when PVRLVN (Keys S0, S1, S2 and S3 open) to booting. In case of failure or when PVRLVN is turned off. The zero relay goes to a safe position, not introducing (adding or subtracting) any voltage to grid.
Voltage regulation is obtained through the activation of static switches, which operate according to the state machine described in the table (Table 1).

Table I. Voltage control states of PVRLVN.

| ***State*** | ***Name*** | ***Description*** |
|---|---|---|
| E0 | Power_ON | Wait 5 seconds after powering |
| E1 | Sum zero | Wait 1 second |
| E2 | Sum ou Subtract | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E2 if status does not change |
| E3 | Zero | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E3 if status does not change |
| E4 | Low sum | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E4 if status does not change |
| E5 | Subtracts little | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E5 if status does not change |
| E6 | Sum middle | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E6 if status does not change |
| E7 | Subtracts middle | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E7 if status does not change |
| E8 | Subtracts a lot | If 0.96 pu < Vout < 1.05 pu<br>Keeps in E8 if status does not change |
| E9 | Outgoing over voltage output | (Overvoltage warning)<br>If Vout > 1.05 pu<br>Keeps in E9 if status does not change |
| E10 | Subvoltage output | (Subvoltage warning)<br>If Vout < 0.96 pu<br>Keeps in E10 if status does not change |

Output voltage regulation follows the state sequence predefined by the state machine and the tap changes to keep the output voltage within the regular range. The voltage to be regulated is the average RMS value of output voltage at a steady state and the reading interval of this voltage is ten minutes, according to the PRODIST regulation. Operation time for changes of static switches taps was set in 4 seconds, enough to avoid successive switching due to repetitive changes of load voltages.
Buck-Boost transformer turn ratio was defined as follows.
1) Output voltage limits are set first, as required by PRODIST, where PVRLVN will be installed;
2) The transformation relations related to the income voltage values range, keeping the values range of the output voltage constant (Fig. 5) as follows:

i. To input voltage 0.96 pu < Vinput < 1.05 pu, the turns ratio is k1 = 1. Here the output voltage is Voutput = k1 x Vinput , operation on the inclined line k1;
ii. Operating on the inclination line k1, when income voltage Vinput < 0.96 pu, the output voltage should be taken to 1.02. In this case, the turns ratio between the output and input is ka = 1.063. Here the output voltage is Voutput = ka x Vinput, operation on the inclined line ka;
iii. While operating on the inclination line ka, the lower limit of input voltage that corresponds to the lower limit of the output voltage is Vinput_lower_limit_ka = 0.96/ ka, so Vinput_lower_limit_ka = 0.903;
iv. Operating on the inclination line ka, when income voltage Vinput < 0.903 pu, the output voltage should be taken to 1.02. In this case, the turns ratio between the output and input is kb = 1.129. Here the output voltage is Voutput = kb x Vinput, operation on the inclined line kb;
v. While operating on the inclination line kb, the lower limit of input voltage that corresponds to the lower limit of the output voltage is Vinput_lower_limit_kb = 0.96/ kb, so Vinput_lower_limit_kb = 0.850;
vi. Operating on the inclination line kb, when input voltage Vinput < 0.850 pu, the output voltage should be taken to 1.02 pu. In this case, the turns ratio between the output and input is kc = 1.2. Here the output voltage is Voutput = kc x Vinput, operation on the inclined line kc;
vii. While operating on the inclination line kc, the lower limit of input voltage that corresponds to the lower limit of the output voltage is Vinput_lower_limit_kc = 0.96/ kc, so Vinput_lower_limit_kc = 0.8;
viii. Operating on the inclination line k1, when income voltage Vinput < 1.05 pu, output voltage should be taken to 0.99 pu. In this case, the turns ratio between the output and input is kd = 0.943. Here the output voltage is Voutput = kd x Vinput, operation on the inclined line kd;
ix. While operating on the inclination line kd, the higher limit of input voltage that corresponds to the higher limit of the output voltage is Vinput_higher_limit_kd = 1.05/ kd, so Vinput_higher_limit_kd = 1.113;
x. Operating on the inclination line kd, when income voltage Vinput > 1.113 pu, output voltage should be taken to 0.99. In this case, the turns ratio between the output and input is ke = 0.889. Here the output voltage is Voutput = ke x Vinput, operation on the inclined line ke;
xi. While operating on the inclination line ke, the higher limit of input voltage that corresponds to the higher limit of the output voltage is Vinput_higher_limit_ke = 1.05/ ke, so Vinput_higher_limit_ke = 1.181.

Fig. 5 presents the transfer function between the Input and Output Voltage of PVRLVN that was used to estimate taps voltage of Buck-Boost transformer, setting on the vertical axis (output voltage in pu) the range demanded by PRODIST, that is , -6% and +5%.

## Communication option and data transmission

Current PVRLVNs have output measurement data, which will allow monitoring via GPRS modem measurements and operating condition of PVRLVN, sending this information to the AES Eletropaulo/AES Sul server. The microcontroller used on the control board is Freescale MC9S08AW60, which has 2 SCIS and 60KB Flash memory, 50KB of which will be available for data storage. Measurement data are sent from the control board PVRLVN to the modem (installed inside the PVRLVN box) via RS232 DB9 serial bus. This modem has a chip that connects to the internet via GPRS (as a 3G modem). Data are sent through this connection to the utility server that receives data from other equipment in the field.

## RESULTS

Tests were carried out to check the performance of the PVRLVN in different conditions of load. The tests consisted of varying the input voltages to the PVRLVNs with no load, linear load from 0 to 30 kVA and non-linear load of 10 kVA. During the tests were recorded voltages and currents at the input and output of PVRLVNs. These values were made at 1 second intervals.

With these tests, it was possible to assess and verify the performance of PVRLVNs under conditions of steady load and verify if the output voltage remained within the range required by PRODIST. Furthermore, it was obtained also output characteristic, ie the transfer function between the output voltage and the input voltage PVRLVN in normal operation.

Table II summarizes the results between input voltages and output in tests relating to the load conditions in empty and full load in a PVRLVN, for a voltage range adjustment 226-246 V. Furthermore, Fig.6 presents the records of a test on PVRLVN for three-phases network, with strong unbalance in one of the input phases and the records of its regulated output, greatly reducing the effect of voltage unbalance.

## CONCLUSIONS

The developed project presented very satisfactory and promising results. This is due to the fact that the PVRLVN can be installed in the low voltage grid quickly and efficiently, correcting the supply voltage immediately after its installation, which is made relatively easily and quickly, solving cases of precarious and critical voltage occurrences.

Results of the tests carried out for different load conditions showed a behavior fully satisfactory. Moreover, even to a condition of unbalanced voltage at the input of PVRLVN phase, this kept its regulated output voltages within the range projected by minimizing grid unbalanced voltage at its output. By submission of this paper, the PVRLVNs tested were referred for field tests and in actual cases, monitored by utilities, but there has not been enough time to include results of field tests in this article.

## REFERENCES

[1] ANEEL, 2011, "PRODIST - Procedures for Electric Energy Distribution in the National Electric System. Module 8 – power quality -. rev.3", National Agency of Electric Energy, Sep.

[2] C. C. B. Oliveira, M. A. Pelegrini, M. M. Filho, L. N. Silva e H. R. Oliveira, 2005, "System for managing voltage measurements" in SISMEDI, VI SBQEE – Brazilian Seminar of Power Quality, Belém, Pará, Aug., pp. 667-674.

[3] F. C. Saraiva Filho, 2002, "Proposed Dynamic recuperator for Voltage Sags", Master Thesis, Polytechnic school - USP, São Paulo. [Online]. Avaliable in: http://www.teses.usp.br/teses/disponiveis/3/3143/tde-10052003-225059/pt-br.php.

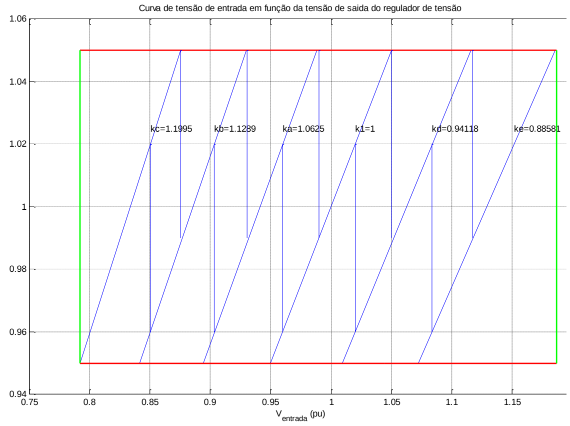


Fig. 5. PVRLVN transfer function.

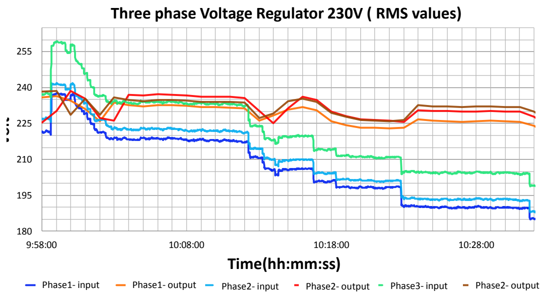


Fig. 6. Test in steady state of a PVRLVN for three-phases networks with unbalanced input voltage.

TABLE II. Input and output voltages obtained on tests for evaluation of voltage regulation.

| Voltage (V) – Regulation per phase | | | |
|---|---|---|---|
| No load | | Full load | |
| Input | Output | Input | Output |
| 190 | 228.5 | 195 | 230.2 |
| 200 | 240.6 | 200 | 235.6 |
| 201 | 226.7 | 203.2 | 226.6 |
| 215 | 242.8 | 220 | 245.6 |
| 220.6 | 235.2 | 223.9 | 235.5 |
| 230 | 245.3 | 230.6 | 242.7 |
| 233.5 | 233.1 | 236.7 | 233.4 |
| 244 | 243.4 | 245 | 242.5 |
| 249.6 | 232.4 | 253 | 233.4 |
| 265 | 246.6 | 265 | 244.8 |
| 265.5 | 230.5 | 270 | 233.3 |
| 280 | 242.9 | 285 | 246.4 |

[4] F. C. Saraiva Filho, S. X. Duarte, J. C. Cebrian, M. A. Pelegrini and R. Tufaniuk, 2011, "Portable Voltage Regulator for Low Voltage Networks". In: The 21st International Conference and Exhibition on Electricity Distribution, Frankfurt.